



The Capabilities of Space Stations

Committee on the Space Station
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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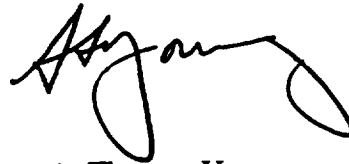
Preface

The Committee on the Space Station of the National Research Council, in considering space station engineering and design issues, found a need for a concise assessment of the capabilities of existing and planned space stations. This report attempts to meet that need by providing information and the important technical parameters for the major crewed space facilities—with emphasis on the Mir Space Station and the International Space Station. Our intent is to provide a data source for easy reference that will enable initial comparisons of the adequacy of these systems to satisfy a complex and evolving set of users' expectations.

Compilation of the data for this report began just prior to the Space Station Freedom redesign with the primary goal of informing the community on the design and capabilities of the Mir and Freedom space stations. As the redesign was carried out by NASA, and after it resulted in the International Space Station, we continued to compile data to document the current designs as well as other existing and historical space platforms (e.g., the Space Shuttle with Spacelab, and Skylab). The committee believes that this summarization of information and parameters supporting space station capabilities will be helpful to those interested in understanding and utilizing the International Space Station.



Frank Lemkey
Chairman, Study on the
Capabilities of Space Stations



A. Thomas Young
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Acronyms and Abbreviations

ACRV	Assured Crew Return Vehicle
AMS	Alpha Magnetic Spectrometer
CDR	Critical Design Review
CIS	Commonwealth of Independent States
COF	Columbus Orbital Facility (European Module)
CSA	Canadian Space Agency
EOS	Earth Observing System
ESA	European Space Agency
EVA	extra-vehicular activity
FGB	Russian acronym, usually translated as Functional Cargo Block
IDR	Incremental Design Review
ISPR	International Standard Payload Rack
ISS	International Space Station
JEM	Japanese Experiment Module
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (of Japan)
PV	Photovoltaic
SAGE	Stratospheric Aerosol and Gas Experiment
SSF	Space Station Freedom
USSR	Union of Soviet Socialist Republics

Introduction

Over the past two years the U.S. space station program has evolved to a three-phased international program, with the first phase consisting of the use of the U.S. Space Shuttle and the upgrading and use of the Russian Mir Space Station, and the second and third phases consisting of the assembly and use of the new International Space Station. Projected capabilities for research, and plans for utilization, have also evolved and it has been difficult for those not directly involved in the design and engineering of these space stations to learn and understand their technical details. The Committee on the Space Station of the National Research Council, with the concurrence of the National Aeronautics and Space Administration, undertook to write this short report in order to provide concise and objective information on space stations and platforms—with emphasis on the Mir Space Station and International Space Station—and to supply a summary of the capabilities of previous, existing, and planned space stations.

In keeping with the committee charter and with the task statement for this report, the committee has summarized the capabilities of five major space platforms. By providing the summary, together with brief descriptions of the platforms, the committee hoped to assist interested readers, including scientists and engineers, government officials, and the general public, in evaluating the utility of each system to meet perceived user needs. Since to date no agreed-on definitive set of requirements for a space station exists, the ability to evaluate existing or proposed capabilities against a complex and evolving set of user expectations may be useful in defining research projects. The committee has not made any judgments on the relative merits of research projects proposed or on the abilities of each space platform to support specific research projects.

This chapter introduces the space stations and platforms considered in the report: International Space Station, the Mir Space Station, the Space Shuttle (with a Spacelab or Spacehab module in its cargo bay), the Space Station Freedom (which was redesigned to become the International Space Station in 1993 and 1994), and Skylab. Skylab, as the only U.S. space station to date, is included because the operational experience gained from this program is relevant, as are the Space Shuttle program and the Space Station Freedom design effort, to NASA's ability to design and develop the International Space

Station. Chapter 2 discusses space station research with emphasis on the anticipated research planned for the International Space Station. Chapter 3 provides data and information on the various space stations and platforms introduced in this chapter and defines the parameters used to describe them. Chapter 4 describes the Mir Space Station and the research that has been performed on board Mir since its launch in 1986. The previous Soviet experience with the Salyut space stations has been superseded by over nine operational years of Mir. Chapter 5 describes the basic aspects of the design and research program planned for the International Space Station. Chapter 6 highlights the differences among the space stations and platforms described in the report, with an emphasis on the differences between International Space Station and its predecessors. The Appendix provides the statements of task for this study and for the Committee on the Space Station.

SPACE STATIONS AND PLATFORMS

The International Space Station

The International Space Station (ISS) has evolved from the space station program of the United States and from the Mir Space Station program of the former Soviet Union and the current Russian Federation. The U.S. program responded to direction from President Reagan in 1984 that called for a space station to be built within a decade. This initial program, which in 1988 was named Space Station Freedom (SSF), was led by the Headquarters of the National Aeronautics and Space Administration (NASA), with design and development separated into four "work packages" awarded to four separate contractor teams managed by four NASA centers. The program has been redesigned and reorganized several times since its inception. The SSF program was a collaborative effort of the United States, the member nations of the European Space Agency (ESA), Japan, and Canada. The Mir program has evolved over a 24-year Soviet and Russian history of supporting long-duration manned presence in low Earth orbit.

In March 1993, congressional and administration responses to projected cost overruns in the SSF program, combined with increased pressures on the federal budget, forced another redesign to cut the cost and reduce the complexity of that design and program. This redesign resulted in Space Station Alpha in September 1993. More Russian components were added to the design, and in late 1993 Space Station Alpha became the International Space Station Alpha. In recent months "Alpha" has been dropped and the program and design are now referred to as the International Space Station. This program is led by a Program Director at NASA Headquarters, Washington, D.C., and carried out by a special NASA program office and a prime contractor, Boeing, located at NASA's Johnson Space Center, Houston, Texas.

The Russian Space Agency will provide the baseline modules for the initial assembly of ISS, the Functional Cargo Block (FCB) module, and a service module similar to the core of the current Mir Space Station, as well as a life-support module,

three research modules, a docking and stowage module, a science power platform with solar arrays, and the Soyuz crew transfer and Progress cargo transport vehicles. The FGB is to be purchased from Russia by Boeing for NASA, and it will be U.S.-owned. NASA will provide the elements of the central truss with hardware for distributed systems providing functions including thermal control and electric power distribution, as well as the large photovoltaic (PV) arrays that will track the Sun as ISS orbits the Earth. NASA will complete the space station configuration with habitation and laboratory modules containing hardware for support of the crew and much of the program's research objectives. Additional laboratory modules will be provided by the ESA and the National Space Development Agency of Japan (NASDA), and Canada will supply a robotic mobile servicing system.

NASA separates the current International Space Station program into three phases. Phase 1, which is primarily the joint use of the Mir Space Station by Russia and the United States, began in 1994 with the flight of the first cosmonaut on the Space Shuttle. Phase 1 has continued during 1995 with the addition of the Spektr module (equipped with some U.S. hardware for research) to Mir and the first docking of the Space Shuttle at Mir. Phase 1 is scheduled to continue through September 1997 with a series of six more Space Shuttle missions to Mir. Phase 2 is to begin in November 1997 with the launch of the first element of the ISS, the FGB. Phase 3 is to begin in 1999, when the U.S. Laboratory Module is scheduled to be fully equipped and able to be used for research. Figure 1 shows ISS in its assembly-complete configuration, and the data in Table 1 in Chapter 3 describe ISS at the end of this phase (scheduled for June 2002). NASA states that ISS will be operable for at least 10 years after its assembly is completed. ISS will be the largest space vehicle ever constructed as well as an unprecedented example of international cooperation on a highly complex project. Construction of ISS's major elements is currently underway.

The Mir Space Station

Mir is the last of 10 space stations built and launched by the Soviet Union, beginning in 1971. It is composed of a core module that was launched in 1986 and several smaller modules that were launched subsequently. Currently, it is operated by the Russian government and the Russian industrial enterprise, RKK (Rocket Space Corporation) Energia. The late-1995 parameters described in Table 1 in Chapter 3, and the configuration shown in Figure 2, are based on the U.S.-Russian program for cooperation in human space missions, which includes improvements of Mir as a precursor to the ISS. The first phase of cooperation between Russia and NASA adds two more Russian-made modules, Spektr and Priroda, equipped with U.S. and Russian payloads as well as new PV arrays providing increased electric power to the Mir. The first of these modules, Spektr, docked with Mir in June 1995. The first of seven planned Space Shuttle missions to dock with Mir, STS-71, took place in June and July of 1995. These missions are to continue through late 1997, just prior to the launch of the

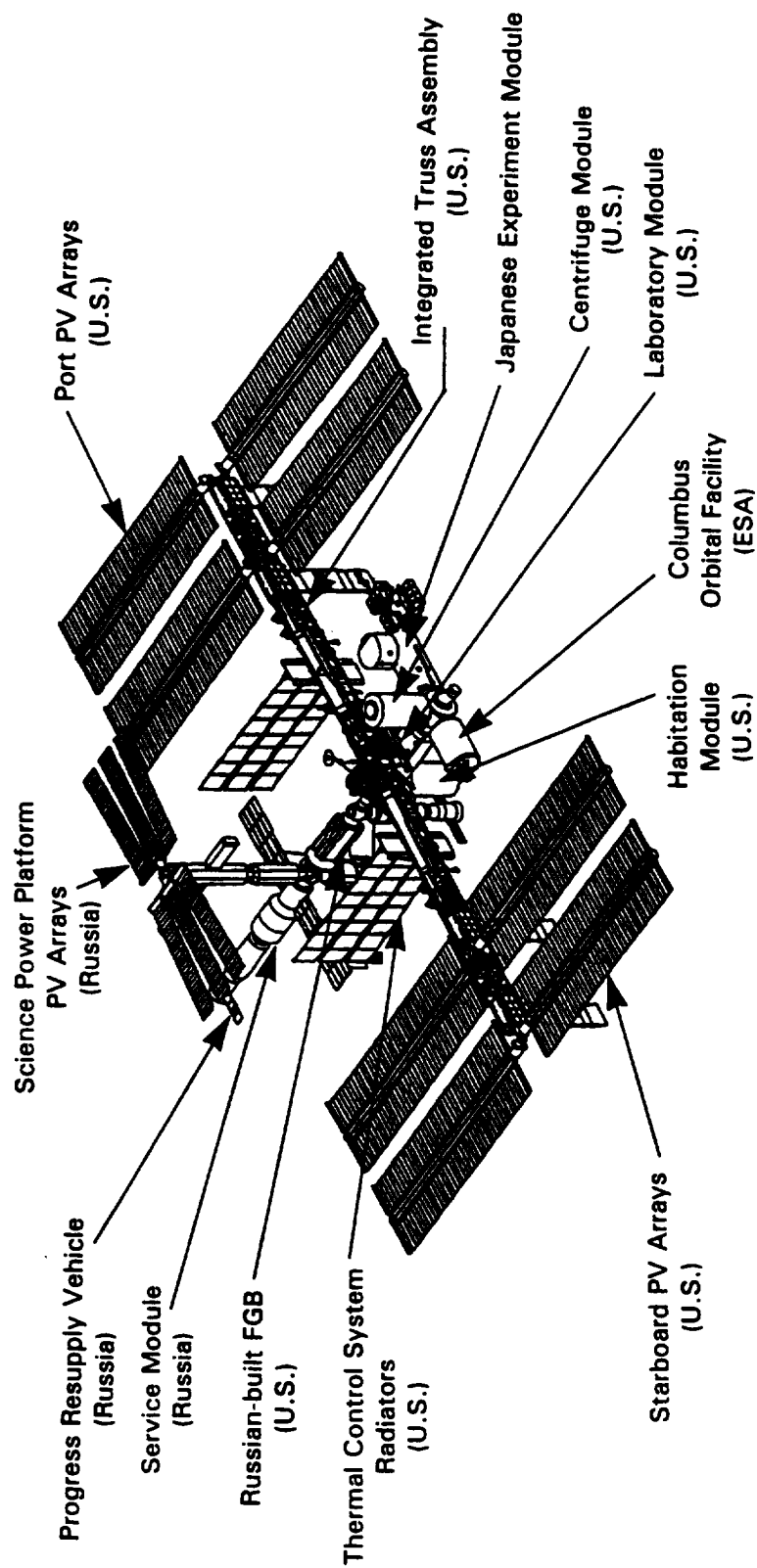


Figure 1 The International Space Station (as described at the March 1995 Incremental Design Review). Source: NASA.

first component of ISS. The information in Table 1 in Chapter 3 describes Mir as it is projected to be after the Priroda module is attached, and Chapter 4 describes the Mir Space Station in detail.

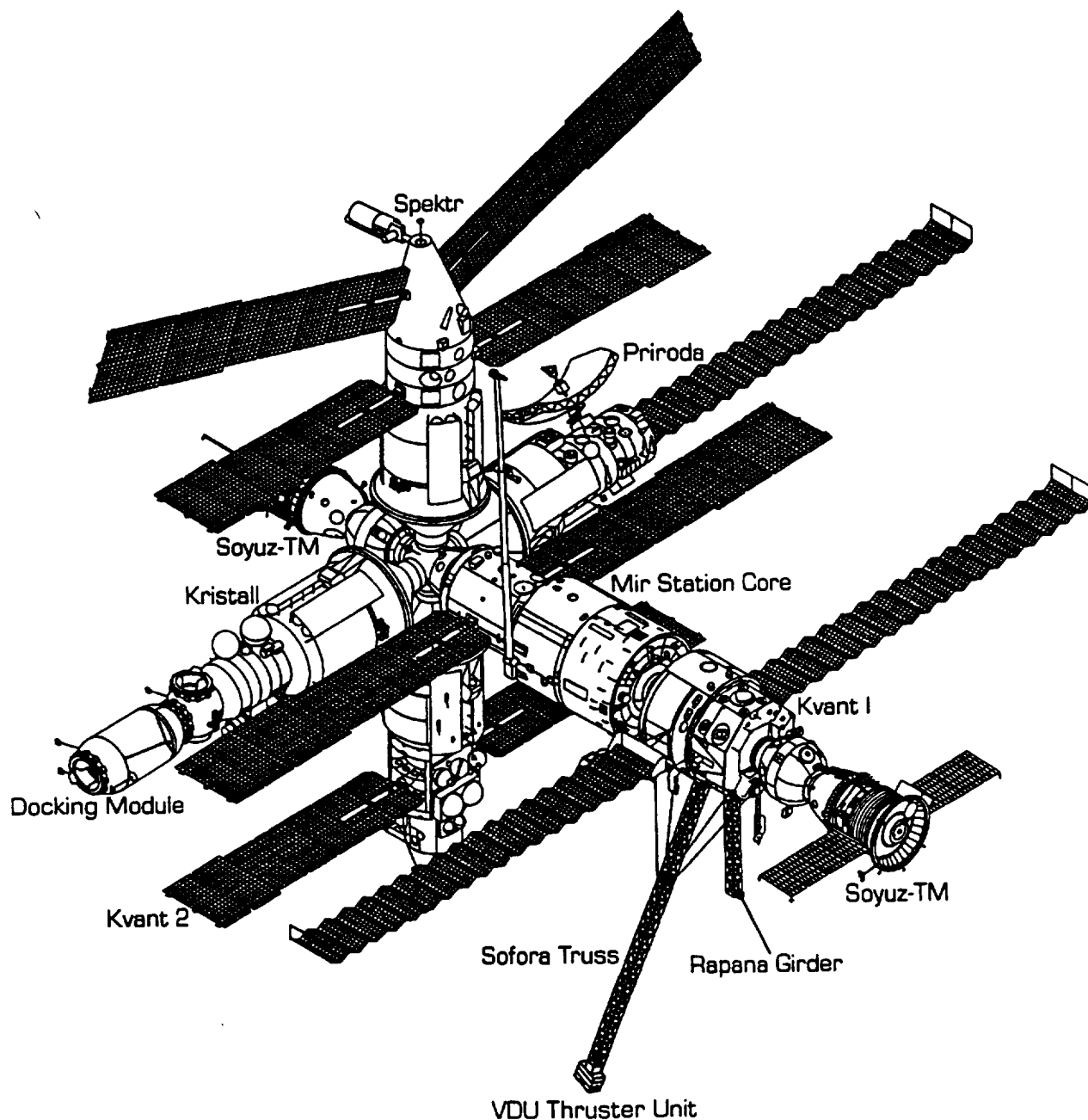


Figure 2 The Mir Space Station (tentative 1996 configuration).
Courtesy of Daniel James Gauthier.

The Space Shuttle with a Spacelab or Spacehab Module

In operation since 1981, the Space Shuttle is the only operating reusable piloted space vehicle. (The Russian Buran vehicle was designed to be reusable and operated with a human crew, but was flown only once without a crew in 1988.) The Space Shuttle information in Table 1 in Chapter 3 describes the existing operational Space Shuttle equipped with a Spacelab module (built by the ESA), or a Spacehab module (built by a private U.S. company), in its payload bay. Both modules are currently used by NASA and will be involved in aspects of the ISS program. The Spacelab and Spacehab modules cannot be deployed free of the Space Shuttle. Illustrations of the Space Shuttle with a Spacelab module and with a Spacehab module are provided in Figures 3 and 4. Although both of these modules greatly expand the research capability of the Space Shuttle, even with a Spacelab or Spacehab in its cargo bay the Space Shuttle does not constitute a true space station (the Space Shuttle cannot stay on orbit indefinitely or provide a site for the permanent presence of humans).

The Spacelab was first flown in 1983, and over 20 Spacelab missions have been completed through late 1995. The Spacelab is modular and configured to meet specific mission requirements. Its four principal components are a module, which is equipped with laboratory equipment for each individual mission and provides a shirt-sleeve working environment; one or more open pallets that expose(s) instruments and materials to space; a tunnel to gain access to the module from the Space Shuttle mid-deck; and an instrument pointing subsystem to enable instruments to be pointed with high accuracy and stability at astronomical targets or the Earth. Twelve Space Shuttle missions have carried the Spacelab Module. In various configurations, Spacelab equipment has been used to conduct research in life and microgravity sciences (using the module), as well as for space science, earth observing science, and commercial research (using a pallet and mission-specific equipment).

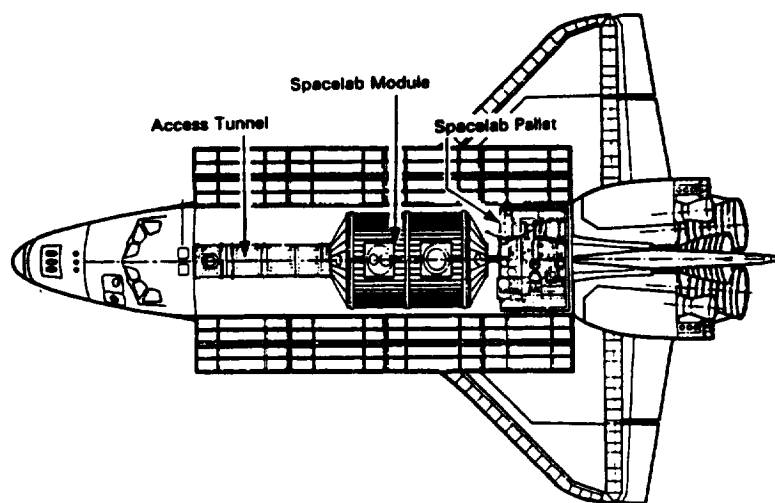


Figure 3 The Space Shuttle with a Spacelab module in its payload bay. Source: NASA.

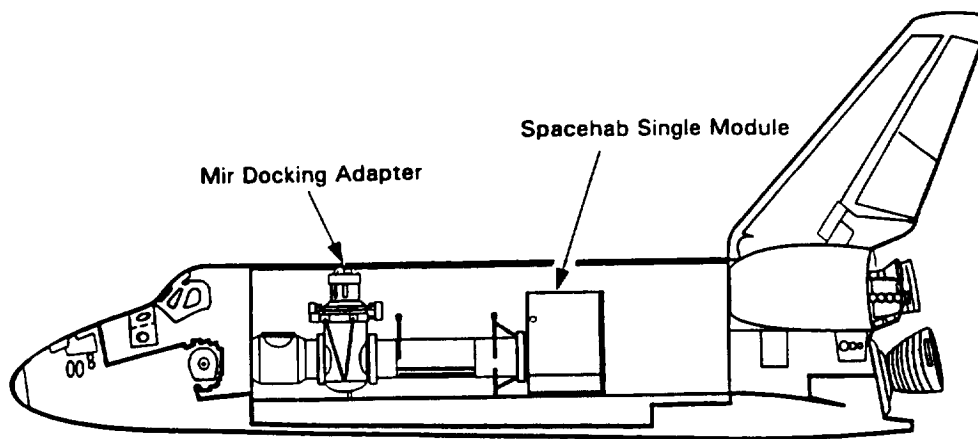


Figure 4 The Space Shuttle with a Spacehab module in its payload bay.
Source: Spacehab, Inc.

A Spacehab module is about 40 percent the size of a Spacelab module and has flown on the Space Shuttle three times: in June 1993, February 1994, and February 1995. The next flight is scheduled for April 1996. It is connected to the Space Shuttle mid-deck through a modified Spacelab tunnel, and the module accommodates various quantities, sizes, and locations of hardware for experiments. Standard experiment accommodations include lockers and racks similar to those used to place experiments in the Space Shuttle mid-deck. The Spacehab module also has an optical viewport, and there is the capability to attach equipment on the exterior of the module. As with Spacelab, provisions exist to deliver power, cooling, and command and data resources to payloads attached inside and outside the module.

NASA plans to use the Spacelab and Spacehab modules to augment the use of Mir and ISS. The Spacelab module has been the site of much of the life and microgravity sciences research performed thus far using the Space Shuttle. If cooperation with Russia on Mir had not been initiated and if ISS were not to be built, the Spacelab or Spacehab would most likely have continued to be used as the primary locales for U.S. research in space using the Space Shuttle. After ISS is completed, the Spacelab and Spacehab modules may be used to perform missions in which a long-term stay in space is not necessary, to carry some pressurized payloads to ISS, or to return samples or materials from ISS to Earth. The capabilities of these modules are also of interest if one seeks to compare current U.S. capabilities with projected future capabilities that will come with ISS.

Space Station Freedom

As stated above, elements of the SSF and Russian plans for a next-generation Mir Space Station were incorporated to create the design for ISS during 1993 and 1994. The U.S.-led space station design was named Space Station Freedom in 1988, and the configuration shown in Figure 5 and described in Table 1 in Chapter 3 is the one that underwent a Critical Design Review (Program Incremental Design Review) in mid-1993. Most of the major components of the SSF design are still planned for implementation on ISS. The SSF program was led by NASA and was a collaborative effort of the United States, the ESA, Japan, and Canada. At the end of the program, in late 1993, there was little Russian involvement envisioned other than the possibility of using Russian Soyuz vehicles for assured crew return.

The four major modules planned for SSF will be included on ISS, although the U.S. Laboratory Module and Habitation Module and the European module have been modified from the SSF design. The Japanese Experiment Module is unchanged. SSF was to be assembled solely from payloads brought to orbit by the Space Shuttle at an orbital inclination of 28.5° to maximize the mass of the payload that could be carried to orbit by the Space Shuttle. SSF had a design requirement to stay operational for 30 years.

Skylab

Skylab was launched by the United States on May 14, 1973, and was inhabited for 28, 59, and 84 days by three different three-man crews. The last crew left Skylab and returned to Earth on February 8, 1974. During the three Skylab missions, research focused on investigations in solar astronomy, life sciences and human factors, Earth observations, astrophysics, and materials science. Before Skylab could be reboosted by a special propulsion module that might have been carried into orbit on an early Space Shuttle mission, Skylab's orbit decayed, and it fell to Earth on July 11, 1979.

Skylab had five major components: a pressurized module or "orbital workshop" that was the main habitable area, a telescope module, a docking adapter, an airlock, and an Apollo command module (for return to Earth). Except for the Apollo command module, Skylab was launched all at once using a Saturn V rocket, and the main module was adapted from the shell for the third-stage rockets and propellant used to propel earlier Apollo missions toward the moon. Skylab is shown in Figure 6, and the information representing Skylab in Table 1 in Chapter 3 describes the space station in its operational configuration. Skylab is the only U.S. space station built thus far. With its unique attributes it provides a basis for comparison for current and future space station designs.

The ability of the astronauts to make repairs during extra-vehicular activity was instrumental in ensuring that Skylab became a habitable and functional space station. Sixty-three seconds into the launch that carried Skylab to orbit without a crew, the meteoroid shield, that was to also shade Skylab's main module, deployed inadvertently and was torn off by atmospheric drag. The loss of the meteoroid shield during ascent led

to the loss of one of Skylab's solar panels, and repairs and modification were conducted by spacewalking astronauts on the first crewed flight.

Figure 7 shows all of the space stations and platforms, described above, on the same linear scale for comparison of the physical dimensions of each space vehicle.

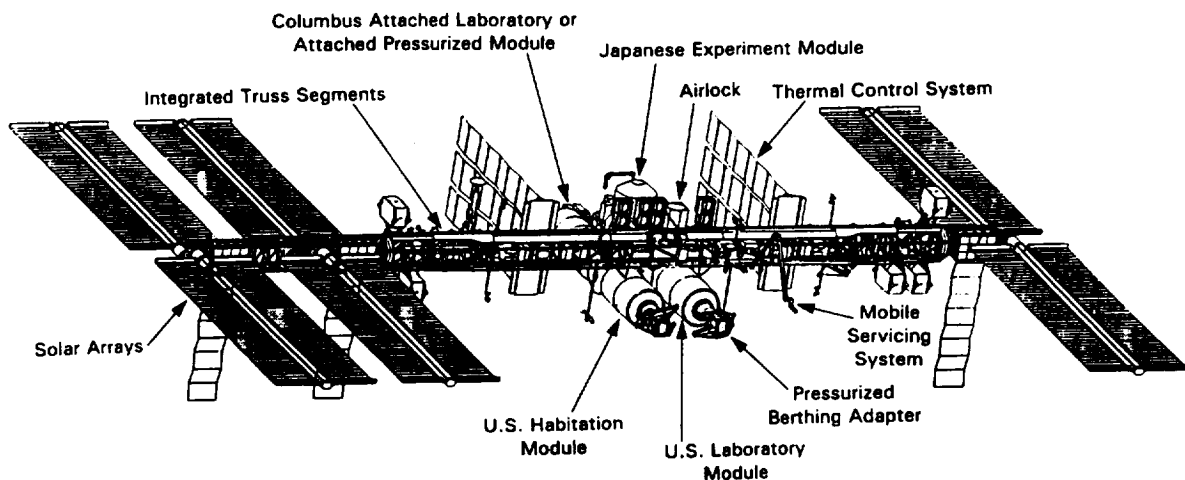


Figure 5 Space Station Freedom (as described at the 1993 Critical Design Review).
Source: NASA.

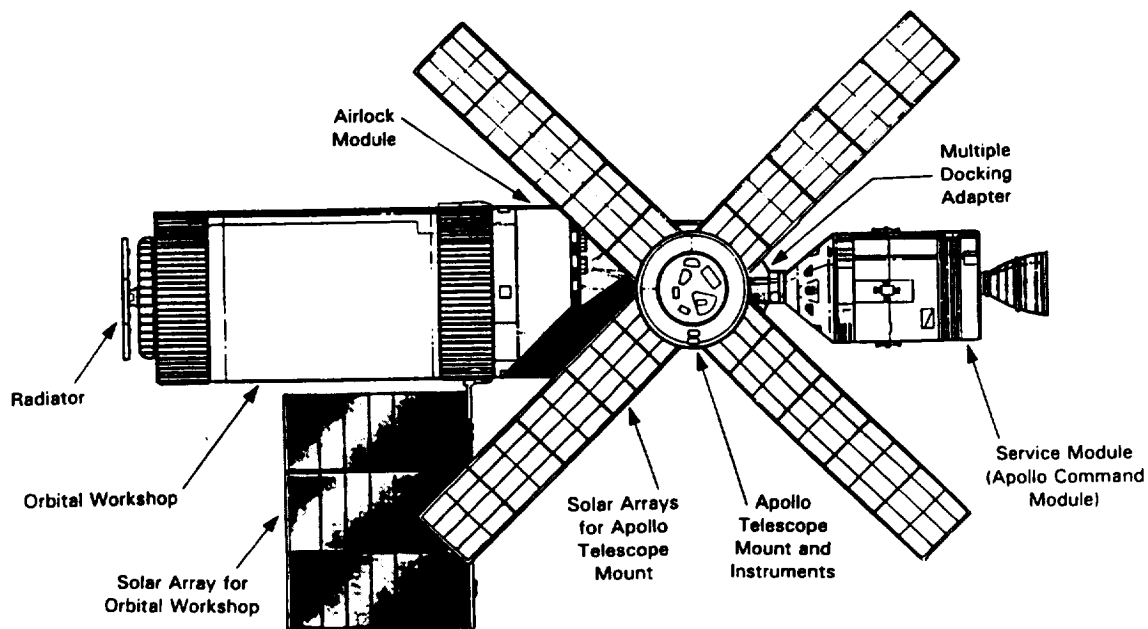


Figure 6 Skylab.
Source: Teledyne Brown Engineering, illustration by Robert A. Sweeney.

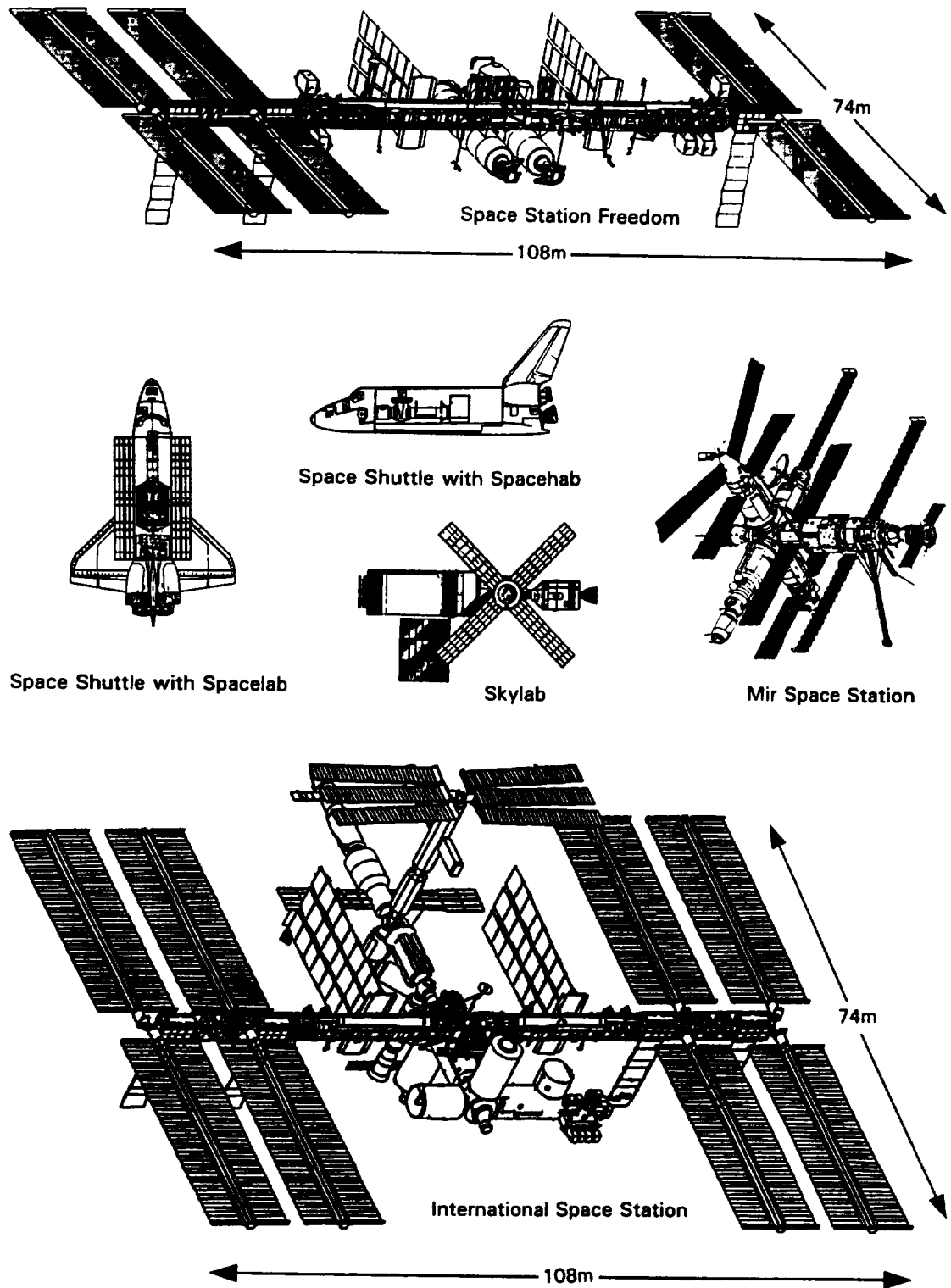


Figure 7 Space stations and platforms to scale (1 cm equals approximately 10 m).

Research Uses of a Space Station

From before the first launch of an artificial satellite, Sputnik 1 in 1957, many ideas have been put forward for potential uses of a space station. These ideas have included using a space station as an Earth and space observatory; a staging point for interplanetary or lunar missions; a laboratory for biomedical, materials science, or physicochemical research; as a center for testing or assembling spacecraft before they are released into Earth orbit; and even as a destination for tourists. For the ISS, NASA and its international partners propose areas of scientific and technological research that require the operational presence of humans and are practical in low Earth orbit. The primary areas for scientific research currently planned for ISS are in the space life sciences, including the study of human adaptation to long-duration space flight and the effect of space flight on the basic biology of plants and animals, and microgravity sciences, including materials science, fluid mechanics, and the study of physicochemical processes such as combustion. NASA and its partners also plan to use the ISS to facilitate engineering research, for example, to aid in the development and testing of new enabling technologies for space in areas such as communications, power generation, advanced life support, and robotic and teleoperated procedures. Space systems, whether manned or unmanned, historically have had a 5- to 10-year cycle from concept to launch and often incorporate technologies that are already nearing obsolescence at the time of launch. NASA intends to use ISS as a proving ground for technology evaluation and insertion, both for replacing systems on ISS and for future spacecraft and missions. Some traditional areas of space science research (e.g., astrophysics, geophysics, and Earth sciences) are not major emphases of current U.S. plans for the use of ISS. NASA envisions that promising commercial activities will be identified as candidates during ISS research and development programs.

This chapter focuses on NASA's work and plans for ISS. European, Japanese, and Canadian work to date on crewed missions has been performed on the Space Shuttle and on Soviet or Russian space stations; their research emphases for ISS are similar to

NASA's. The Russian plans for ISS payloads are not available, but Russia has indicated that the research areas prominent aboard Mir will be continued on ISS.¹ Chapter 4 covers Russia's work on Mir over the last 9 years. The research described below pertains only to that performed on crewed space platforms, not on research performed using unmanned scientific spacecraft in Earth orbit or interplanetary space. Describing in detail what has been achieved on the various space platforms, including over 70 Space Shuttle missions and over 19 man-years on Mir, and other space platforms such as the Salyut space stations and Skylab, was outside the scope of the study.

Research opportunities planned for ISS are discussed briefly in the following sections. The bibliography at the end of the report contains references to detailed reports from the National Research Council on several of these topics and to other relevant reports and books detailing the breadth and scope of space research in low Earth orbit.

SPACE LIFE SCIENCES

Life sciences research in space has had two thrusts: (1) the investigation of the influence of gravity on basic biological processes, and (2) assessment of the impact and limitation on space operations resulting from the physiological deconditioning associated with weightlessness.²

The first thrust, the basic study of gravitational biology, requires long-duration exposure of plants and animals, the ability to repeat experiments, a well-equipped space laboratory, and a specialized crew. Unexpected alterations in living organisms and biological samples, ranging from cell cultures and plants to the nervous systems of mammals, have been observed in short-duration flights. Very little work has been done with artificial gravity levels between 0 and 1 g, a capability that could be provided by an onboard centrifuge, or with multiple-generation studies on the effects of space flight on normal development using animals and plants that reproduce relatively quickly.

The second thrust, space operations medicine, may make progress through the use of ISS for long-duration missions with a large number of crew members. ISS will have a crew of six astronauts and cosmonauts. All crew members are likely to be available as subjects for some investigations, and this increased opportunity to gather data may provide the means for increased insight into the adequacy of proposed exercise protocols and other countermeasures to enable people to return to Earth in good condition after a prolonged mission. Experience on Mir has shown that crew members can withstand long-term space flights (including up to 14 months—longer than projected in the crew rotation plans for ISS) and return to Earth in generally good health. But the ISS, with its larger set of more advanced biomedical devices, will provide the opportunity to test new

¹ See Grigoriev, 1995

² For detailed information on space life sciences see the several relevant reports of the NRC's Space Studies Board and its Committee on Space Biology and Medicine from 1987 to 1994.

techniques to diminish the physiological adaptations to microgravity that prove deleterious upon return to Earth (e.g., reduced bone density) and enable increased insight into the body's overall adaptation to microgravity conditions. Results may eventually contribute to long-term goals related to human exploration of the solar system beyond Earth orbit, as well as to biomedical insights applicable to terrestrial applications in the treatment of disease.

In addition to the capabilities described above that contribute to the ability to perform life sciences research in space, other parameters that enable space life sciences research include adequate electrical power, specialized biomedical equipment and facilities, significant crew time for research, a crew including biomedical professionals, an ability to send data to and communicate with researchers on the ground and the ability to preserve biological specimens and return them to Earth on a regular basis.

MICROGRAVITY SCIENCES

Through thousands of years of observing physical phenomena and theorizing as to cause and 400 years of organizing data scientifically to explain observed facts, gravity has always been present. It has only been in the last 35 years that more than a few seconds of scientific observations in the absence of gravity have been possible and even fewer years since the first coordinated series of microgravity scientific experiments were carried out in space. Since some initial work on Apollo and Skylab missions, NASA has performed only relatively short-term research in microgravity on the Space Shuttle, placing payloads in the Spacelab module, cargo bay, and mid-deck lockers. Nevertheless, the field is still in its early phases of development. ISS will provide both the opportunity for longer-term (e.g., 15 days to several years) microgravity experimentation and the ability to rework and repeat experiments until consistent and reproducible results are received.

Through the use of ISS, opportunities will exist for microgravity experimentation in fluid mechanics and transport phenomena, combustion, biotechnology, materials science and processing, and microgravity physics. To sustain the development and utilization of inherently complex flight hardware and experiments capable of yielding high-quality data in both the space life sciences and microgravity sciences research, the following factors will be important: maintenance of the quality of the microgravity environment, early involvement of the scientific community in experiment planning, and shortening of the cycle from designation of a principal investigator to flight of a selected experiment. The general capabilities necessary for conducting microgravity research in space are similar to those necessary for life sciences research. However, microgravity research is considered to derive greater benefits from gravity or acceleration levels as near as possible to zero because the physicochemical processes studied are generally

more sensitive to higher or fluctuating gravity levels than are biological systems (within the ranges seen on an orbiting space platform).³

SPACE SCIENCES

The traditional space sciences pursued by NASA include astrophysics, planetary science, and space physics (primarily the study of the Sun, interplanetary space, and the magnetospheres and upper atmospheres of planets). At the present time, NASA has limited plans and funding for the use of ISS as a space sciences observation and data acquisition platform, but has selected one space science experiment to be conducted as an attached payload on ISS. NASA plans to continue to rely on dedicated unmanned spacecraft for detailed investigations of the solar system, near-Earth space, and the galaxy and universe beyond our solar system. The U.S. and Soviet Union have both developed technologies to enable observations from spacecraft in low Earth orbit, including crewed space stations. In the 1970s many observations of the Sun, other astronomical bodies, and the Earth were made from Skylab and during the 1980s and 1990s observations have been made from the Space Shuttle. As discussed in Chapter 4 of this report, the Mir Space Station has also been extensively utilized for such observations. The availability of ISS as a permanently manned spacecraft can be expected to provide opportunities for its use as a platform for the mounting of instruments or experiments to respond rapidly to unforeseen opportunities for space sciences observations. A precedent for this kind of potential utilization of ISS is the use of Skylab in 1973-1974 as a site for observations of the comet Kohoutek.

EARTH OBSERVATIONS AND SCIENCES

A low orbital inclination of 28.5° (which resulted in a restricted ability to view most of the temperate areas of the Earth), combined with funding problems, led to the elimination of the Earth observing payloads from the Space Station Freedom (SSF) design. With this low inclination orbit, none of the partner nations in SSF would have been able to see or study most of their countries from orbit. In the United States, only southern Florida, southern Texas and Hawaii would have been overflown, and none of Japan, Canada or Europe would have been overflown. Looking toward the horizon, data would have been able to be gathered somewhat north and south of the actual flight path, as far north as Georgia in the United States and southern Japan in Asia. An earlier

³ Scientific and programmatic issues related to microgravity research are detailed in an NRC (1995) report entitled *Microgravity Research Opportunities for the 1990s*. Especially relevant is Chapter 8, "Flight Opportunities and Challenges."

version of the U.S. space station program included a separate unmanned space platform that would have been launched into a polar orbit in order to be able to observe all of the Earth's surface over time. This portion of the program was eliminated during a 1991 redesign of SSF.

Now that the orbital inclination of its successor, ISS, has been set at 51.6° , more of the Earth, including most of Asia and Europe and all of the United States except Alaska, will be in view. As described in Chapter 4, the Mir Space Station, at the same inclination, has been used and continues to be used to conduct a significant Earth observation research program. Although funding limitations preclude the initiation of a major NASA Earth sciences program from ISS, NASA has made some preliminary plans for such research. The Earth Observing System (EOS), a part of NASA's Mission to Planet Earth concept, consists of a series of polar-orbiting and low-inclination satellites intended to provide long-term global observations of land surface, biosphere, solid Earth, atmosphere, and oceans. As part of the Mission to Planet Earth, a single two-part experiment, the Stratospheric Aerosol and Gas Experiment (SAGE) III, will fly one part on ISS with a second part placed on a polar-orbiting spacecraft scheduled for launch in 1998.

SPACE TECHNOLOGY DEVELOPMENT

Many technologies for space platforms have been developed and tested on the ground prior to launch. The availability of ISS as a long-term, permanently crewed, orbiting testbed will support the demonstration of subsystem modifications and new concepts and technologies. Technology tests on ISS may provide useful results without jeopardizing spacecraft performance, as might be the case if the first use of a new technology were in a critical application. Continuing engineering research on topics including materials exposure, fluid processes, on-orbit assembly, electric power generation and storage, debris protection, food and water supply and recycling, data management, crew-return and supply vehicles, and space systems operation has the potential to lead to more efficient and less-expensive operations in space. These research initiatives, together with rapid advances in the capabilities and availabilities of new commercial off-the-shelf technologies, may produce upgrades to subsystems of the initial ISS configuration, as well as new capabilities. For example, commercial computer hardware and software technology will support onboard sensor data processing, converting the sensor-provided bit stream into usable information and eliminating the requirement for high-capacity data downlinks.

Using ISS to prove new technology may help increase the use of new technology in unrelated space endeavors. An example of this kind of technology research concerns the high cost of command and control, including facilities and manpower. These could possibly be reduced by greater reliance on autonomous, onboard spacecraft operation, but there has been understandable reluctance on the part of the spacecraft controller to give

up authority to an unproven onboard system while retaining responsibility for the health of a spacecraft. Functioning as a testbed, ISS could demonstrate autonomous operations at reduced risk.⁴

Many factors will determine the ability to pursue technology development research, including the ability to bring large payloads to orbit and to integrate as appropriate outside or inside the pressurized volume of a space station, the electrical power available, the size of the space station and facilities present onboard, a crew with appropriate expertise and time to conduct extended research programs, the ability to involve researchers from many countries, and the ability to communicate with researchers on the ground.

COMMERCIAL RESEARCH

The projected commercial utility of a space station has varied widely over the last 10 years. It is now generally assumed that although some useful products (e.g., pharmaceuticals or thin-film materials for use in electronics) may be produced on a future space station, it is unlikely that any endeavor identified to date as a potential source of revenue could be cost-effectively pursued if the prorated cost of the resources and infrastructure employed were taken into account. High costs have made the commercialization of any enterprise involving humans in space an elusive goal.

The international character and openness of the ISS program may well foster an increase in the commercial relevance of the work performed onboard by making it easier for companies to fly their payloads in space. However, it is currently not possible to justify development of a space station by projecting financial return from commercial enterprises. The true utility of a space platform to support commercial use will only be understood after such a station is operational and a realistic assessment of potential can be made.

⁴ Identification of additional engineering and technology transfer opportunities in the ISS program has recently been addressed by the NRC Committee on the Use of the International Space Station for Engineering Research and Technology Development.

Space Station Parameters

Summary information on the key parameters of the space stations and platforms introduced in Chapter 1 is provided in Table 1. In this table, 33 parameters are listed, and for each parameter a numerical value or other data point is provided for ISS (at assembly complete), Mir (with the Priroda module attached), the Space Shuttle with a Spacelab module, the Space Shuttle with a Spacehab module, the plans for Space Station Freedom (which was redesigned into ISS starting in 1993), and the capabilities that existed on Skylab. The 33 parameters listed are quantifiable or are other objective factors that, taken together, provide a summary of the overall capabilities of each space vehicle.

Including other parameters in the table to further characterize the space platforms was considered but rejected. In general, parameters were rejected by the committee when: (1) the parameter was one that tends to vary widely throughout a given time period, and including a single value in the table would have been inaccurate but including a wide range of values would have been uninformative (e.g., CO₂ or humidity level in cabin atmosphere); (2) the parameter was potentially misleading (e.g., design life); or (3) reliable data were not available for every space platform in the table (e.g., additional data on the microgravity environment).¹ In order to increase the value of the data to the

¹ The following examples are representative of additional parameters considered by the committee.

Design life was not included because it is not as useful in describing a real space station as one might think. This is partially due to the fact that, unlike most planetary or Earth-orbiting spacecraft, a space station regularly visited by astronauts or cosmonauts can be upgraded and repaired during its time in space. The Mir Space Station was designed for seven years on orbit, but it has been used for over nine years and is expected to be used for two more. On the other extreme, NASA planned to use Space Station Freedom (SSF) for 30 years, but current plans call for using its successor, the ISS, for only 10 years. One consequence of the change from 30 to 10 years is that the projected lifetime cost of the program has been greatly reduced, but it is likely that ISS will be used for more than 10 years if it is still functional and there continue to be good reasons to continue to use it after 2012. In general, including design life as a parameter would have lead to misconceptions that the SSF would have been usable exactly three times as long as ISS will be, or that Mir would have been usable only until 1993 (if stated in 1986).

reader, a brief definition explaining each parameter has been placed in the table above the data provided on the space stations and platforms. Because the capabilities of Mir and ISS are more directly relevant to present and future plans for research in space, information in addition to that provided in Table 1 regarding these two space stations is provided in more depth in Chapters 4 and 5, respectively.

The data and information provided in Table 1 are derived in part from published documents that appear in the bibliography, unpublished sources such as NASA, and industry presentations and information releases, as well as from communications with NASA and industry personnel. The data have been assessed through the best technical judgment of the committee and are based on the best information available at the time this report was written.

Definitive data regarding microgravity levels and volumes within certain microgravity levels was sought but was not obtainable (e.g., for ISS projections are available, but they are ellipsoids based on computer models that are not readily converted to a conclusive description of useful volumes for research payloads).

The committee considered using the International Standard Payload Rack (ISPR) as a parameter to describe the volume and facilities available for research but found that it was not possible to do so as the parameter was only completely applicable to Space Station Freedom. The racks in a Spacelab are different from the lockers in a Spacehab, and both are different from ISPR racks. ISS will have ISPRs in the U.S., European, and Japanese modules, but the Russian modules will have a different configuration to accommodate pressurized payloads and are not likely to be able to be fitted with payloads designed for ISPRs. Furthermore, because the ISPR provides more than just volume (e.g., standard power, data, and mechanical interfaces) the committee decided that inventing a new payload volume parameter such as an "ISPR equivalent" would be more misleading than illuminating.

Table 1 begins on the following page.

TABLE 1 Space Station Parameters

Parameter	Mir (in early 1996, with all modules)	International Space Station at assembly-complete (based on 1995 IDR data)	Space Shuttle with Spacelab Module	Space Shuttle with single Spacehab Module [double Spacehab Module]	Space Station Freedom at assembly-complete (based on 1993 CDR data)	Skylab (1974)
Program Overview						
Countries Involved	<p>The countries providing significant contributions to the assembly and operation of the space station. Potential advantages of a large number of national participants include availability of multiple launch systems, efficient use of national space technology specialties, increased safety through independent analyses, and cost sharing. Potential disadvantages include conflicting operational objectives, incompatibility of systems, political instabilities and wavering commitments, multiple funding approval authorities, and cost increases due to integration issues. In addition to their association through ESA, some ESA countries have separate agreements describing additional involvement in the programs (e.g., France and Germany with Russia regarding Mir, and Italy with the United States regarding ISS).</p>					
	Russia, U.S., ESA countries	U.S., Russia, ESA countries, Japan, Canada	U.S., ESA countries, Japan	U.S., Italy, Japan	U.S., ESA countries, Japan, Canada	U.S.
Projected Availability Date	<p>The date at which permanent habitation can be initiated.</p>					
	through at least late 1997	1998 (to be completed in 2002)	habitable while the Space Shuttle remains in orbit	habitable while the Space Shuttle remains in orbit	1999 (to be completed in 2000)	not applicable (last used in 1974, deorbited in 1979)
Research Emphases	<p>The types of research that have been emphasized in the development and planned utilization of the space station. Normally, these topics will include the five basic orbital scientific disciplines: life sciences, microgravity sciences, space sciences, Earth observations, and space technology development. Different modules of the space station may be specially outfitted to support only one or a few of these disciplines.</p>					
	astrophysics, Earth observations, microgravity sciences, life sciences, technology and commercial research	life sciences, microgravity sciences, technology and commercial research	life sciences, microgravity sciences, commercial and technology research	commercial and technology research, life sciences, microgravity sciences	life sciences, microgravity sciences, technology and commercial research	life sciences, solar astronomy, Earth observations, astrophysics, microgravity sciences, technology research

Configuration and Dimensional Parameters						
Total Pressurized Volume (m ³)	The measure of the interior space of the facility in which the crew and most experiments must fit. The volume of the space station will determine the nominal long-term and maximum short-term crew sizes and will directly affect the design of the life-support, electrical power, and thermal control systems. Volume tends to be minimized to reduce the size and cost of the space station, but larger volumes are conducive to crew productivity and well-being and permit greater experiment flexibility.					
	410	1,120	166 (93 Spacelab only)	104 [135] (31 [62] Spacehab modules only)	680	354
Total Modules (including nodes and crew-return vehicles)	The number of separate air-filled elements brought together in space to form the standard permanent habitation and working areas. Each module must be equipped with one or more docking ports, and many support systems (e.g., electricity, propellant, communications) require module interfaces. Modular assembly permits the construction of larger space stations than could be outfitted on and then launched from Earth. Modular assembly also allows replacement of major components, future reconfiguration of the space station, and the ability to maintain the station in the event of a serious breach or malfunction in one area. A large number of modules can reduce overall space station mass efficiency and can impose new safety hazards.					
	9	17	2	2	8	2
Total Mass (kg)	The total terrestrial weight of the space station, including modules, deployed structures, internal equipment, and consumables. The total mass reflects the size, complexity, expense, and difficulty of assembling and operating a space station in orbit. The cost of spacecraft, modules, and space hardware are often a function of their mass, and launch costs are generally a direct function of mass.					
	140,000	419,000	about 13,700 for equipped Spacelab (about 110,000 for the Space Shuttle)	about 5,000 [9,070] for equipped Spacehab (about 110,000 for the Space Shuttle)	281,000	90,000
Length x Width (m)	The overall maximum dimensions of the assembled space station. This parameter often does not include small appendages (e.g., antennas), but may include the attachment of temporary logistics vehicles.					
	33 x 41	109 x 85	6.9 x 4.1 (length x diameter)	2.8 x 4.1 [5.6 x 4.1] (length x diameter)	107 x 74	36.1 x 28
Maximum Pressurized Diameter (m)	The widest internal dimension perpendicular to the long axis of the pressurized module. This parameter is normally limited by the space launch systems employed for orbiting space station components.					
	4.2	4.3	4.1	4.1	4.3	6.6
Number of Docking Sites	The number of places where visiting spacecraft can dock with the space station. This number does not include docking ports that are occupied by permanently attached elements. Docking sites may not be of a standard or universal design (i.e., the space station may possess incompatible docking sites for different classes of spacecraft).					
	4	6	1	1	2	2
Hatch Diameter (m)	The internal diameter of the docking port connecting the space station modules and spacecraft through which crew and materials may safely pass. Although most hatches will conform to a standard size, special smaller or larger diameter hatches may be available for experimental work or extra-vehicular activities.					
	0.8, 1.0	1.39, 1.0	1.0	1.3	1.39	0.7

Parameter	Mir (in early 1996, with all modules)	International Space Station at assembly-complete (based on 1995 IDR data)	Space Shuttle with Spacelab Module	Space Shuttle with single Spacehab Module (double Spacehab Module)	Space Station Freedom at assembly-complete (based on 1993 CDR data)	Skylab (1974)
Launch and Orbital Parameters						
Associated Launch Vehicle	The space launch systems required to deploy the space station components, to ferry crews to and from the space station, and to afford all necessary logistics functions. These space launch systems may be expendable or reusable and manned or unmanned. Multiple launch systems, including vehicles and launch complexes, for each category will enhance overall space station support reliability.					
Projected Number of Launches to Assemble	Soyuz, Proton, Space Shuttle	Space Shuttle, Soyuz, Proton, Zenit, Ariane 5	Space Shuttle	Space Shuttle	Space Shuttle	Saturn V, Saturn IB
	The number of flights necessary to carry the specified components of the space station to orbit. To permit appropriate comparisons, this parameter does not include logistics flights that only carry expendable supplies or crew return vehicles to the space station prior to completion. The numbers below do not include flights wholly dedicated to resupply or utilization during assembly.					
Maximum Payload-Up Mass (kg)	6	44 (27 U.S., 15 Russian, 1 European, 1 undetermined)	not applicable	not applicable	27	1
	The standard maximum mass of useful payload that can be delivered to the space station for each designated support spacecraft/launch system. This parameter includes both the capacity of heavy-lift launch systems employed to orbit space station modules and the internal carrying capacity of logistics spacecraft that do not become a permanent part of the space station. The former will influence the number of missions needed for assembly of the space station, while the latter will affect the number of annual missions necessary to support space station operations.					
Maximum Payload-Return Mass (kg)	2,700 (Progress), 11,600 (Proton), 15,740 (Space Shuttle)	15,740 (Space Shuttle), 2,700 (Progress), 11,600 (Proton), 4,750 (Progress M2), 9,000 (Ariane 5)	4,600 inside Spacelab Module	2,200 [4,100] inside Spacehab Module	17,600	exact data not available (~ a few hundred kg), the pay- load was limited to the volume available for stowage in the Command Module
	The maximum mass of materials, excluding crew members, that can be returned to Earth from the space station for each designated support spacecraft. The ability to return materials to Earth is essential to the completion of many scientific and technological experiments. Materials no longer required on the space station and that need not be returned to Earth may be ejected from the space station and allowed to be destroyed during atmospheric reentry.					
Maximum Payload-Return Mass (kg)	150 (Raduga), 17,100 (Space Shuttle)	17,100 (Space Shuttle)	4,600 inside Spacelab Module	2,200 [4,100] inside Spacehab Module	17,600	300

Inclination (degrees)	The orbital inclination of the space station, defined as the angle between the space station's orbital plane and the Earth's equator. In practice, the orbital inclination of a space station cannot be smaller than the latitude of the most-northern launch facility used to support assembly of or logistics for the space station. For a given launch site, the amount of useful payload that can be delivered to a space station decreases as the orbital inclination increases. Maximum launch vehicle capacity is achieved when the orbital inclination of the space station is the same as the latitude of the launch site.				
	51.6	51.6	varies with mission	varies with mission	28.8
Mean Orbital Altitude (km)	The average altitude of the space station as it completes one revolution about the Earth. The mean altitude may vary during normal and logistics operations or during fluctuations in the Earth's atmospheric density, primarily caused by solar activity. Normally, the space station is maintained in nearly circular orbit (i.e., the difference between the closest [perigee] and farthest [apogee] approaches to the Earth during each orbit is small).				
	400	400	varies with mission	varies with mission	430
Assured Crew Return Vehicle	The spacecraft attached to the space station for the express purpose of returning the crew members to Earth at any time. The crew return vehicle may or may not be part of normal logistics operations. The vehicle or vehicles at a minimum must be capable of immediately supporting all of the crew members in emergency situations (major space station system failure or medical emergency) and of returning them to Earth in a timely manner. Multiple crew return vehicles permit the emergency return of crew members with medical problems without completely abandoning the space station.				
	Soyuz	Soyuz (Space Shuttle and Soyuz for routine return)	not applicable (Space Shuttle)	not applicable (Space Shuttle)	Soyuz or new U.S. vehicle
					Apollo Command Module
	Crew Parameters				
Permanent Crew Capability	The ability to keep a space station inhabited for an indefinite period of time. For a space station to be able to support crews for extended durations, the facility and its infrastructure must be able to furnish expendables (food, air, water, propellants, short-lived equipment, etc.) at a rate exceeding consumption.				
	yes	yes	no	no	no
Typical Crew Size (persons)	The number of people who normally inhabit the space station and conduct scientific and technological experiments or perform space station control and maintenance functions. The crew size will normally vary for short periods during crew rotations (handovers) and logistical missions. The typical crew size is directly limited by the capacity of the life-support and electrical systems, the resupply network, and the size of the space station itself.				
	3	6	up to 7	up to 7	3
Crew Duration	The number of continuous days a crew will spend on board the space station. The crew duration may vary due to mission requirements and logistical capacity. Individual crew members may conduct extended stays on board the space station for biomedical and psychological purposes.				
	4-6 months typical (but up to 14 proven)	3 months standard	up to 15-20 days	up to 15-20 days	3 months standard
					28, 59, and 84 days

Parameter	Mir (in early 1996, with all modules)	International Space Station at assembly-complete (based on 1995 IDR data)	Space Shuttle with Spacelab Module	Space Shuttle with single Spacelab Module [double Spacelab Module]	Space Station Freedom at assembly-complete (based on 1993 CDR data)	Skylab (1974)
Crew Parameters (continued)						
Primary Constraint to Longer Missions	For space stations that are not permanently inhabited, the reason why crews cannot stay on orbit longer. The principal technical constraints are normally the supply of electrical energy and other consumables.					
	none technical	none technical	energy (dependent on the Space Shuttle)	energy (dependent on the Space Shuttle)	none technical	not designed for resupply
Crew Time for Research Use (person-hrs/day)	The total person-hours each day that the crew can devote to research-oriented work. Other activities which limit crew time for users are space station maintenance activities, meals, hygiene chores, personal time, sleep, and mandatory exercise periods.					
	about 7.5	about 23	about 30-40	about 30-40	about 18	about 18
Power and Operations Parameters						
Total Power (kW)	The maximum electrical power capable of being generated and utilized by the space station under normal power conditions. This is the power available for all uses, including essential housekeeping requirements and non-essential activities, e.g., experiments. Space stations are primarily dependent upon the conversion of solar energy into electrical energy to meet daily power requirements. Various storage devices are used to maintain minimum power levels during periods of transit through the Earth's shadow or of low angles between the sun and the orbital plane of the space station. Electrical power is one of the major limitations to space station utilization efficiency.					
	<25	110	7.7	3.15	71	18
User Power (kW)	The amount of electrical power normally available to the crew for non-essential uses such as powering laboratory equipment. This power level will, in part, determine the number and the combination of experiments that can be performed simultaneously.					
	4.5	~50	3.5 to 7.7	3.15	30	3
Voltage (V dc)	The electrical potential at which the power is supplied to systems and outlets. Spacecraft voltage is usually provided as direct current (e.g., 28 Volts dc) by the main electrical bus, but alternating current can be generated via electrical converters at the subsystem or experiment level. High voltage levels can increase the complexity and the safety requirements of the electrical distribution system.					
	28.5	120 and 28	28	28	120	28
Solar Array Area (m²)	The amount of active surface area on all solar arrays capable of converting solar energy directly into electrical energy. The area of the solar arrays is thus directly proportional to the amount of power that can be used for housekeeping and experimental purposes. The type of solar cell material (e.g., silicon or gallium arsenide) will determine the power density of the array (i.e., the amount of power generated per square meter).					
	430	~3,000	0	0	~1,800	165

Data Rate (down rate, in Mbps)	A measure of the capacity of the space station's communications system to send data to the Earth. In general, the higher the data rate, the larger the required transmitter power and antenna size. Data rates can also be limited by the route which is selected (e.g., direct to ground to a main receiving station or to an auxiliary receiving station or via intersatellite relays). Data rate requirements can be reduced in some cases by onboard data processing.				
	7	50	45	16	<1
Steady State Acceleration Near Center of Mass (in $g \times 10^{-6}$)	The degree of microgravity normally existing near the center of the space station. Microgravity levels for low altitude, unmanned Earth satellites may experience one-millionth of the force of gravity at the surface of the Earth. Crew activities (e.g., normal movements and exercising), spacecraft dockings, equipment operations, and orbital maneuvers will reduce the quality of the space station's microgravity environment. The levels shown below may be considerably higher (e.g., up to 100 times higher for the Space Shuttle) during especially energetic on-orbit maneuvers and is also higher at high frequencies. Low microgravity environments are especially desirable for many microgravity science experiments.				
	50-250	1 (requirement)	1-10	1-10	1 (requirement)
Video Up and Video Down (yes/no & yes/no)	The ability of the space station to receive or to transmit video communications. This capability is useful not only for scientific research (e.g., space science and Earth observation, but also for daily communications with the space station crew).				
	yes & yes	yes & yes	no & yes	no & yes	no & yes
Water Recycled (yes/no)	The ability of the space station to extract water from its environment (human waste, atmosphere, experiments, etc.) and to recycle it in a useful (potable or nonpotable) manner. Recycled water can also be used to maintain the space station's atmosphere and to perform attitude and altitude control. Normally, different systems are designed to recycle water from the various sources. The greater the efficiency of the space station's water recycling systems, the lower the logistical requirements for supplying additional water.				
	yes	yes	no	no	no
Atmospheric Pressure (atmospheres)	The nominal maintained pressure of the space station's environmental control system. Most space stations operate with a pressure equivalent to sea level on Earth (1 atmosphere). This standard facilitates the support of both man and machine on the space station.				
	.67 - 1.34	1	1	1	.34
Nitrogen/Oxygen² (percent)	Percent of nitrogen and oxygen in the space station atmosphere. When the atmospheric pressure is maintained near one standard Earth atmosphere, the nitrogen and oxygen composition of the atmosphere is also approximately that found on Earth. If the atmospheric pressure is reduced, the relative percent of oxygen must be increased.				
	79-60/21-40	78/22	78/22	78/22	26/74
Cabin Temperature (° Celsius)	Permissible range of temperature maintained within the space station. The actual temperature will fluctuate depending upon the atmospheric humidity and pressure. Some areas of the space station may have elevated or reduced temperatures depending upon experiment requirements or by-products.				
	5-40	18-27	18-27	18-27	13-32

²Trace gases are discussed in the NRC (1994) report, *Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants, Volume I*.

The Mir Space Station

For 24 years Soviet/Russian space stations have demonstrated the technology required to maintain a human presence in Earth orbit and have proven the utility of manned experiments across a wide spectrum of scientific disciplines. Since the launch of Salyut 1 in 1971, seven Soviet space stations have supported more than 11,000 man-days (30 man-years) of on-orbit experience. (Three other space stations were lost during or shortly after launch during 1972-1973 and were never occupied.) The current Mir Space Station represents the culmination of this technological evolution and embodies many of the operational concepts adopted by the ISS. The evolution of Soviet space stations is shown in Figure 8.

ASSEMBLY AND DESIGN

Assembly of the Mir Space Station began in February 1986 with the launch of the first element: the Mir core module. Originally anticipated for a seven-year life span, the Mir orbital complex was to consist of six permanent modules serviced by manned and unmanned logistics spacecraft and to be completed by 1990. However, after seven years in orbit only four of the six permanent modules (Mir in 1986, Kvant 1 in 1987, Kvant 2 in 1989, and Kristall in 1990) with a total mass of more than 70 metric tons had been launched. The launches of the remaining two modules were repeatedly delayed. As part of Phase 1 of the ISS program, the precursor phase of international cooperation using the Mir and the Space Shuttle prior to beginning the assembly of ISS, additional modules are being docked to Mir. The Spektr Module was docked in June 1995, and the final Mir module, Priroda, is scheduled for docking in December 1995. Both modules are equipped with U.S. research payloads and equipment as well as Russian equipment.

During its first nine years in orbit, the Mir Space Station hosted 17 main expeditions, which accumulated nearly 19 person-years of activity with crews representing nine countries or organizations (Afghanistan, Austria, Bulgaria, ESA, France, Germany, Japan, Syria, and the United Kingdom), in addition to the many

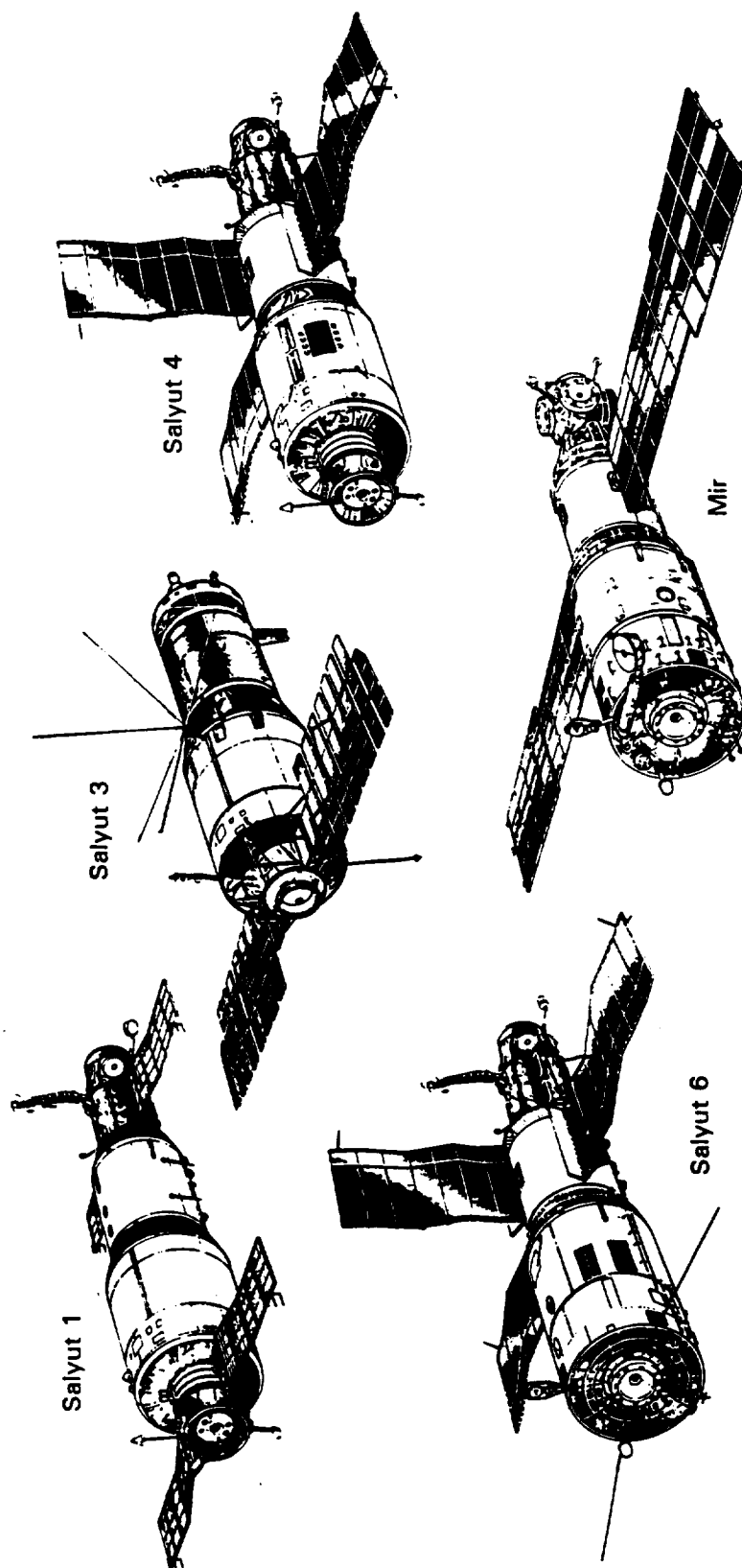


Figure 8 The evolution of Soviet space stations. Source: Johnson (1994).
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republics of the former USSR and the now Commonwealth of Independent States. A record 14-month mission was completed in March 1995 by Dr. Valeri Polyakov, who spent a total of 22 months on the orbital complex. The facility has been permanently manned since September 1989, and by April 1995, had received 71 different spacecraft of eight types. As shown in Table 2, an average of 7-8 missions have been flown annually from 1986 to 1994 without a launch failure (67 Soyuz and 4 Proton launch vehicles in all); all spacecraft have successfully rendezvoused and docked with the complex. More than 90 successful dockings have been accomplished (including those dockings associated with repositioning spacecraft for logistical reasons).

To support the significant logistical requirements of the Mir Space Station (about 10-12 metric tons per year), the previously proven Soyuz-T manned transport and the Progress automated cargo ferry were enhanced to create the current Soyuz-TM and Progress-M variants. The Soyuz-TM spacecraft debuted in 1986 and had carried 20 crews of 2-3 people to the Mir Space Station by the spring of 1995. Capable of independent flight for several days or being docked with Mir for more than six months, the 7.1-metric-ton Soyuz-TM design will be modified to serve as an ISS crew-return vehicle. The Soyuz-TM is rated as able to return up to three cosmonauts to an Earth site on land or at sea.

The 7.3-metric-ton Progress-M freighter can resupply the Mir Space Station with more than 2.5 metric tons of material, including food, air, water, propellants, clothing, equipment, replacement parts, and a wide assortment of other cargo. More than 70 Progress (1978-1990) and Progress-M (1989-present) vehicles have been launched, and each one has successfully docked with its intended space station (Mir or one of its Salyut predecessors). Most dockings are automated (a crew need not even be on board the space station), but a cosmonaut can take control and perform the operation manually, if necessary. In 1990 the Raduga reentry capsule was introduced, permitting suitably equipped Progress-M spacecraft with the ability of returning up to 150 kg of material to

TABLE 2 Launch and Resupply History of Mir, 1986-1994

YEAR	Modules	Soyuz	Soyuz-TM	Progress	Progress-M
1986	Mir	1	1	2	0
1987	Kvant 1	0	3	7	0
1988		0	3	6	0
1989	Kvant 2	0	1	2	2
1990	Kristall	0	3	1	3
1991		0	2	0	5
1992		0	2	0	5
1993		0	2	0	5
1994		0	3	0	5
TOTAL	4	1	20	18	25

Earth. Progress-class spacecraft have also been used to perform special scientific experiments after completing their missions to Mir (e.g., deployment of large antennas or solar reflectors). At their end-of-life, Progress-M vehicles are loaded with refuse and destructively deorbited, usually over the Pacific Ocean.

The Mir core module, which serves as the principal space station control element, contains the main computers, communications equipment, kitchen and hygiene facilities, and primary living quarters. A small airlock is available for experiments or for the release of small satellites or refuse. The forward end of the Mir core module is configured with five docking ports (one forward and four radial) to receive logistics spacecraft and to attach four large permanent modules. Although the Mir core module's main propulsion system has not been operational since the arrival of Kvant 1 in 1987, this central module serves as the principal propellant storage unit and assists in controlling the attitude of the entire space station.

The smaller Kvant 1 module contains a suite of scientific instruments for astrophysical observations and materials science experiments as well as attitude control devices (gyrodynes) designed to improve the stability of the space station and to reduce propellant consumption. It is also the site of two girders (Sofora and Rapana) erected by cosmonauts on the outside of Kvant 1. While both structures are used for a variety of experiments, the taller (15 m) Sofora tower was equipped in 1992 with a roll-control engine, the precursor to a Russian unit now under development for ISS.

The Kvant 2 spacecraft is called the "additional equipment module" due to its large amount of equipment created for improving living conditions and operations in the overall complex. Kvant 2 carried electrolysis units (Elektron and Vika) to provide oxygen from recycled water; a new, large-capacity water supply system (Rodnik); two separate water regeneration systems; new sanitation facilities; a new shower; and a compartment designed to enhance extra-vehicular activities (EVAs). Several life science, materials science, and Earth observation instruments are also installed on Kvant 2.

The Kristall module was created to expand experiments in five major scientific fields: materials processing, biotechnology, biological studies, Earth observations, and astrophysical research. As its name implies, the module's major equipment was dedicated to materials science investigations. Kristall was also fitted out with two additional universal docking ports (APAS-89), which evolved from the APAS-75 docking system created for the Apollo-Soyuz Test Project in 1975. This new system was tested successfully in 1993 and was used by Space Shuttle mission STS-71 in the first Shuttle-Mir docking in June, 1995.

The addition of both the Spektr and Priroda modules by the end of 1995 will increase the utility of the Mir Space Station. Spektr has recently been added to Mir, and Priroda is scheduled for launch before the end of 1995. Both modules are equipped with a variety of Earth observation instruments, as well as other experiments for materials science, space technology, or space science. Equally important will be the increased power generation capability they will provide. Their arrival will essentially complete the Mir assembly process, resulting in an orbital facility of approximately 140 metric tons

(see Chapter 3 for the principal parameters describing the Mir Space Station at this stage). Current plans call for the Mir Space Station to be operated until at least late 1997, when construction of ISS will commence.

During the nine-year operation and maintenance of the Mir Space Station, EVAs have proven invaluable and highly effective. Forty EVAs were performed in the 1987-1994 period (average of five per year) for a total of 344 man-hours outside the space station. In addition to permitting the installation and removal of scientific experiments on the exterior of the orbital facility, EVAs have been used to correct a docking problem with the Kvant 1 module; to repair scientific instruments, a rendezvous antenna, an EVA hatch, and a Soyuz-TM thermal control system; to test manned maneuvering units; to install additional solar arrays; and to construct the Sofora and Rapana trusses.

RESEARCH ON MIR

The Mir Space Station provides opportunities for wide-ranging scientific and technical experiments. Often, the Mir operational program is structured to concentrate on specific scientific disciplines (e.g., Earth observations or materials sciences) for several days or weeks to increase the efficiency of crew support. During the period 1992-1993, the relative proportions of investments in experiments were technical experiments (40 percent), remote sensing and environmental experiments (24 percent), technological and biotechnological experiments (15 percent), astrophysics experiments (13 percent), and medical and biological experiments (8 percent). The following sections highlight some of the hundreds of pieces of major equipment and instruments which have been operated on the Mir space station.

Space Life Sciences

The principal life sciences experiments surround the physical well-being of the Mir Space Station crews, including initial adaptation to the microgravity environment, physiological changes during short- and long-duration missions, and readaptation to a 1-g environment upon return to Earth. The extensive USSR/CIS experience on space stations has led to the refinement of a number of practices and devices that can either monitor the physiological effects of near-weightlessness or be employed as countermeasures to prevent unnecessary and potentially harmful effects.

In part by trial and error, Russian medical experts have determined that two hours of strenuous exercise (normally one hour in the morning and one hour in the evening) are necessary to maintain acceptable circulatory and muscle conditioning. A treadmill and a bike (Veloergometer) play a central role in this regimen. In addition, "penguin suits" (coveralls with elastic straps) may be worn up to eight hours a day to place axial loads on the body. Prior to the return to Earth, the Chibis pneumatic vacuum suit is worn for

extended periods to help redistribute blood to the lower body. Several medical monitors (e.g., Aelita, Gamma 1, and Lyulin for use inside Mir and Beta-8 for use during EVAs) are available to compile the extensive medical database required for research into the effects of prolonged human space flight. An ultrasonic cardiograph (Argument) has also been employed by and on Mir cosmonauts.

Life sciences experiments with plant and animal life have been many and varied during the history of Mir operations. In 1989 the Inkubator 2 apparatus arrived with the Kvant 2 module and has been used in several attempts to hatch Japanese quail eggs and monitor their development under microgravity conditions. Unfortunately, the first such experiment in March 1990 fell far short of its goals, lasting only 22 days out of a planned 233-day investigation, when all the hatchlings failed to adapt and perished. Later experiments with older quail proved more successful.

The Magnitogravistat installation was used to monitor the effects of varying both gravitational and magnetic forces on plant growth, including the interaction with bacteria in the soil. Several types of botanical units using normal soil or hydroponics (e.g., Bioterm, Fiton, Rost, Svet, and Svetoblok-M) have been tested with one goal: to discover the means of sustaining plant growth as a possible source of foodstuffs in a closed ecosystem, particularly on interplanetary voyages. Cellular fusion was the subject of experiments with the Rekomb bioreactor in 1990. Another bioreactor, Vita, has supported cellular cultivation experiments.

Microgravity Sciences

In addition to research concerned with the effects of microgravity on living organisms as noted above, numerous materials processing, biotechnology, and fluid-flow experiments have become routine for each Mir expedition. A large number of diverse electric furnaces (e.g., Gallar, Korund-1M, Krater-V, Kristallizator, Optizon, Zona-2, and Zona-3) have been operated using conventional and halogen lamp heating. Some of these devices qualify as pilot production units, for example, capable of producing 5 cm diameter gallium-arsenide crystals. Semiconductor samples from the Zona-2 and Zona-3 electric furnaces (temperatures up to 1800 °C and 1400 °C, respectively) can be 3 cm in diameter and 30-36 cm in length. Optizon was designed to produce silicon monocrystals via crucibleless melting techniques, and Krater-V can be used for week-long experiments to produce zinc-oxide crystals.

Biotechnological experiments, particularly those employing electrophoresis (e.g., EFU Robot, Ruchey, and Svetlana devices) and protein crystal growth (e.g., Aynur and Biokrist devices) have been popular on Mir. Electrophoretic experiments have included purification of blood and the production of high-quality interferon and anti-influenza preparations. Mir experience has shown that the purity and separation quality of electrophoretic experiments under microgravity conditions can be more than 100 times better than those on Earth. The Ruchey device is a higher productivity unit and utilizes a

technique of moving fluid through an electric field to permit four methods of electrophoresis. Due to sample storage requirements and the need to examine the samples as soon as possible, biotechnology experiments are often conducted on Mir shortly before a normal crew rotation so that samples can be returned to Earth in a timely manner. Some protein crystal growth experiments have taken as long as two and a half months to complete.

Examinations of fluid flow in space have used the Pion-M to investigate thermocapillary convection and Kvant 2's Volna 2 apparatus. Pion-M, which was transferred from the Salyut 7 Space Station to the Mir Space Station in June 1986, uses a transport tray to observe nonuniformities in fluids injected with markers. Better understanding of fluid flow under microgravity conditions is vital to the design of water distribution systems, propellant transfer systems, and the like. Chemical reactions in microgravity have been the subject of experiments with the Biryuza apparatus.

Space Sciences

Mir space science encompasses a number of scientific disciplines, including astrophysics, solar system physics, and geophysics. The arrival of the Kvant 1 module with its 800-kg, multinational Roentgen X-ray Observatory and the USSR-Swiss Glasar ultraviolet telescope at Mir in April 1986 was fortuitous because it closely followed the Supernova eruption in the Large Magellanic Cloud in late February of that year. The Roentgen X-ray Observatory contained four main instruments: (1) German HEXE high-energy scintillation spectrometer, (2) USSR Pulsar X-1/Spektr-3 X-ray telescope, (3) ESA Sirene-2 high-pressure gas scintillation proportional spectrometer, and (4) UK-Netherlands TTM coded mask imaging spectrometer. The Vedma X-ray spectrometer was developed by Germany for Kvant 1 to conduct observations of charged particle radiation in magnetic fields of neutron stars. In 1988 the Rozhen electro-optical device with a Paralax-Zagorka image intensifier was first used for astrophysical observations. Kristall's arrival in 1990 brought the Glasar 2 ultraviolet telescope and the Marina telescope to study cosmic radiation.

Several instruments have been installed in the Mir Space Station to observe various solar-terrestrial phenomena and interactions. The Mariya magnetic spectrometer on Kvant 1 measures high-energy electron and positron fluxes in near-Earth space. In January 1990, two cosmonauts on an EVA installed the Arfa-E device on the exterior of Kvant 1 to investigate the Earth's ionosphere and magnetosphere by injecting electron beams perpendicular to the geomagnetic field. Similar experiments have been conducted in conjunction with other, unmanned, Earth-orbiting satellites. During the testing of the Soviet-manned maneuvering unit in 1990, one of the cosmonauts carried the Spin-6000 instrument to measure the radiation of the Mir Space Station induced by the constant bombardment of cosmic radiation.

Earth Observations and Sciences

Mir's orbital inclination of nearly 52° enables it to view most of the planet, including the most densely populated zones, and thus serves as an excellent platform for Earth observation. Its extended longevity in orbit also permits the evaluation of potential regional or global changes. Besides frequent observations of the Earth by trained cosmonauts, the Mir Space Station offers an array of sophisticated and high-quality instruments to record this vital information. From hand-held Hasselblad cameras to high-precision topographic camera systems (KAP-350, KATE-140, and Sever) to multispectral (MKF-6MA) and high-resolution (Priroda 5) cameras to optical, infrared, and multispectral spectrometers (MKS-M, MKS-M2, ITS-7D, Skif, and Spektr-256), the Mir Space Station offers a full range of Earth observation devices. Typical photographic resolutions vary from the 5 m Priroda 5 to the 10-15 m MKF-6MA to the 50 meter KATE-140. Also available are photometers (EFO-1 and Terra) and other instruments (AFM-2 and PCN) used especially for atmospheric studies and a video spectropolarimeter (Gemma 2) for multipurpose remote sensing.

Mir's multifrequency observation capabilities will be increased significantly with the attachment of the Priroda module which will carry multiband scanning radiometers (IKAR-D and IKAR-N), a panoramic radiometer (IKAR-P), several spectrometers (ISTOK-1 IR, MOZ-OBZOR, MSU-E, MSU-SK, and OZON-M), a synthetic aperture radar (Travers), a French lidar (Alisa), and the refurbished German modular optoelectronic multispectral stereo scanner (MOMS) previously flown on the U.S. Space Shuttle. Together these instruments will support a six-point research program for (1) determination of the atmosphere-ocean system characteristics, (2) measurements of the land local characteristics, (3) measurements of optical characteristics of the atmosphere, (4) investigation of the sea surface roughness state, (5) comparison of radiation and reflection characteristics of the sea surface in the microwave range, and (6) measurements of the concentrations of trace gases in the atmosphere.

Space Technology Development

Perhaps the broadest area of Mir scientific research is in the development of space technologies for future applications, both in space and on the Earth. Space technologies include not only specific systems or components but also research that will lead to new or improved systems or components. Many of the systems operating on Mir today are the result of years of testing and development on earlier Soviet space stations.

Major Mir systems include the Elektron and Vika electrolytic water decomposition facilities; the gyrodynes for station attitude control; the Igla and Kurs rendezvous systems; the APAS-89 docking system; the Luch satellite data relay system; the Argon 16B, Salyut 5B, and EVM computer systems; the Burs, Korona, and Tranzit-A communications and data transmission systems; the ASPG-M movable instrument

platform; the Orlan-DMA EVA suit; the Ljappa module relocation system; the Rodnik water supply system; the YMK manned maneuvering unit; the VDU roll-control engine unit; the Strela exterior crane; and the Vozdukh atmospheric CO₂ removal system.

A number of space technology experimental devices include the Sofora and Rapana girders, the Yantar electron beam evaporizer, the Electrotopograph-7M used to study protective and dielectric construction materials, the TIGR holographic television system for studying the degradation of space station portholes, and a large number of investigations into the effects of the near-Earth environment on various materials such as ferromagnetics, polymers, and composites (e.g., Meduza, Ferret, Danko, Etalon-D, and Plenk-3).

The International Space Station

The ISS will be the largest and most advanced laboratory ever built for research in space. It is intended to return scientific, technological, political, and economic benefits to its international partners (United States, Russia, Canada, Japan, and certain members of the European Space Agency—Belgium, Denmark, France, Germany, Italy, Netherlands, Norway, Spain, and the United Kingdom). The partner governments have agreed to cooperate in the detailed design, development, operation, and utilization of this permanently manned civil space station consistent with an intergovernmental agreement signed in 1988 for Space Station Freedom and officially extended in 1994 to include Russia.

ASSEMBLY AND DESIGN

Originally envisioned as Space Station Freedom, the current U.S. portion of ISS resulted from U.S. government executive and legislative direction to NASA to significantly reduce cost, maintenance, and complexity while expanding the opportunities for cooperation with Russia. The current program's capability, cost, schedule, and risk containment have been significantly improved by Russia's inclusion (e.g., in the multiple paths to orbit provided by three different Russian launch systems, Russia's long-term orbital experience, and its self-docking spacecraft). A new management approach that incorporates a single prime contractor (Boeing) to the NASA program management team is intended to integrate and control the key aspects of the program, such as cost, schedule, and technical requirements. The ISS program is carried out by a program office and management and engineering teams at NASA's Johnson Space Center, with the Program Director and a relatively small staff at NASA Headquarters.

At completion, the ISS configuration will consist of 11 permanent, major pressurized modules along with the support systems to provide power, thermal control, life support, and all other necessary functions. The configuration of ISS when completely assembled is shown in an exploded view in Figure 9. Seven modules will be primarily

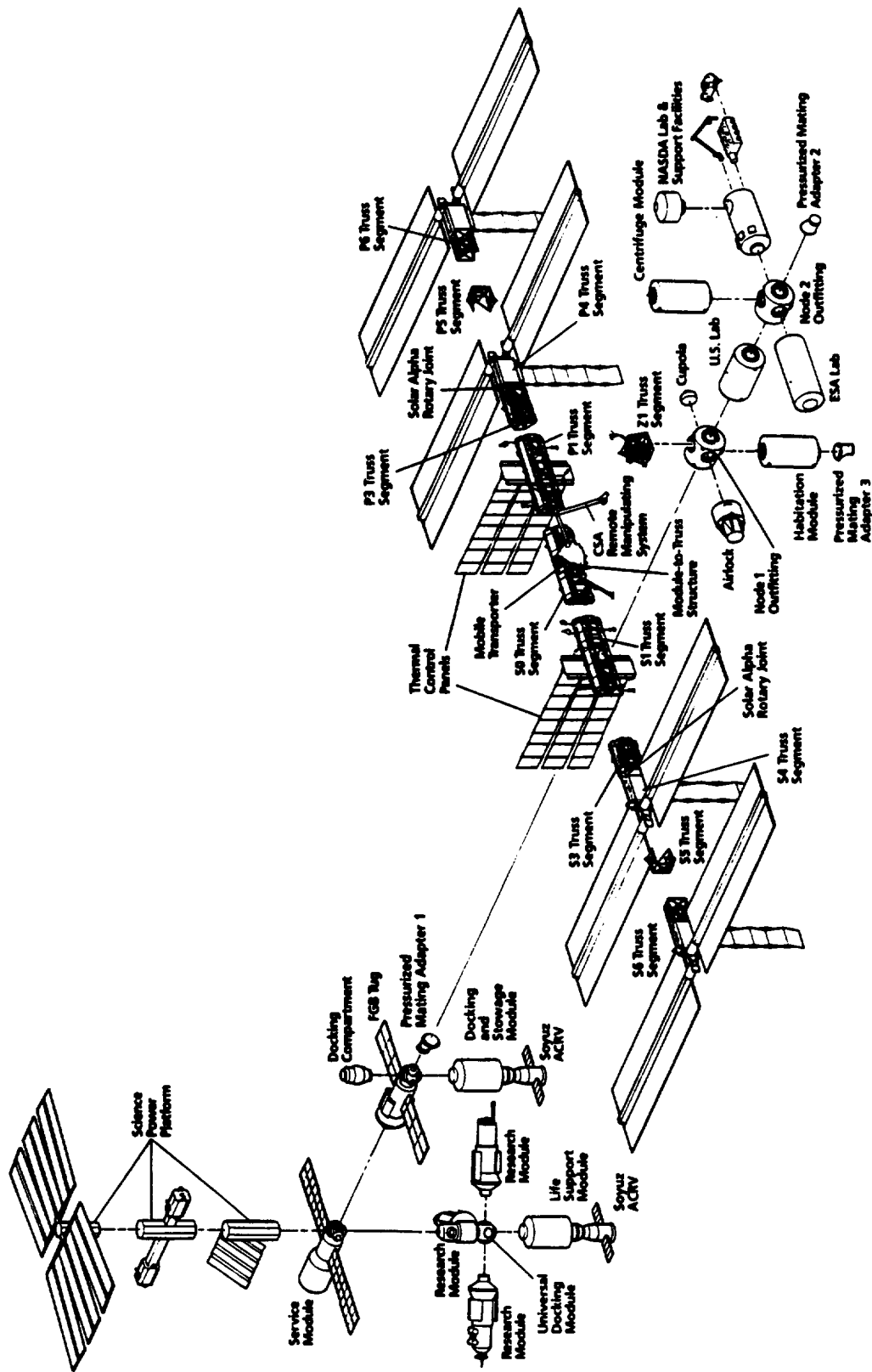


Figure 9 Exploded view of the completely assembled International Space Station (shown as described at the March 1995 Incremental Design Review). Source: McDonnell Douglas Aerospace.

dedicated to research: the U.S. Laboratory Module, the Centrifuge Module, the ESA's Columbus Orbital Facility (COF), the Japanese Experiment Module (JEM), and three Russian Research Modules. At this time, these modules have varying levels of design maturity (e.g., the JEM is essentially unchanged from the configuration planned for Space Station Freedom, while the COF has been redesigned to be smaller, and multiple designs and configurations are being considered for the Centrifuge Module). Three modules will serve primarily as crew habitats and provide life-support functions: the U.S. Habitation Module, the Russian Service Module, and the Russian Life Support Module. The Russian Functional Cargo Block (FGB) module will provide propulsion, navigation, and attitude control during the early assembly phases. In addition to the modules listed above, two Soyuz-TM vehicles (or further upgraded Soyuz vehicles) will be present at all times to facilitate crew rotation and provide the capability for rapid return to Earth of all crew members in case of emergency. The ISS will be resupplied mainly by the Russian Progress-M vehicle and a successor vehicle currently in development, the Progress-M2. The Progress-M and M2 will dock often at ISS, and there will likely be one or more of these spacecraft attached much of the time. The Space Shuttle will also dock at ISS to rotate crew members and to deliver payloads and supplies. In addition to the permanent modules and visiting spacecraft listed above, the ISS also features several nodes between the modules that provide additional pressurized volume. A summary of the assembly schedule is shown in Table 3.

TABLE 3 Milestones in the Assembly of the International Space Station

Milestone	Scheduled Date	Launch Vehicle	Comments
Launch of FGB tug, first element of ISS	November 1997	Proton	FGB will be Russian-built, but U.S.-owned
Launch of Node 1 and adapter to FGB	December 1997	Space Shuttle	First Space Shuttle launch in assembly process
Launch of Russian Service Module	April 1998	Proton	Provides first crew habitat
Launch of first Soyuz - TM	May 1998	Soyuz	Provides crew return vehicle, permanent crew of 3 possible
Launch of U.S. Laboratory Module	November 1998	Space Shuttle	Provides initial U.S. research capability
Launch of Japanese Experiment Module	March 2000	Space Shuttle	Provides additional research capability for Japan and U.S.
Launch of European Module (Columbus Orbital Facility)	September 2001	Ariane 5	Previously planned for launch on Space Shuttle
Launch of U.S. Habitation Module	February 2002	Space Shuttle	Provides more living space and facilities for crew
ISS Configuration Complete (launch of second crew transfer vehicle and last outfitting flight in assembly sequence)	June 2002	Space Shuttle	Permanent crew of 6 possible

NASA plans to assemble ISS in 44 launches, with approximately 28 launches using the U.S. Space Shuttle, 15 using Russian launch vehicles, and one using Europe's Ariane 5, in a phased assembly sequence over five years. Twenty-nine additional U.S. and Russian flights during the assembly sequence are projected as necessary to rotate crew members and for resupplying the space station with expendables such as food and propellant.

The basic design for the completed ISS can be viewed as a reconfigured Space Station Freedom joined to a previously planned next-generation Mir Space Station. The ISS design uses approximately 65-75 percent of Space Station Freedom's hardware and systems and also uses proven robust hardware from Russia such as the Service Module, the self-contained FGB tug, the hardware for automated rendezvous and docking, the Soyuz-TM and Progress-M, and the Soyuz launch vehicle.

ISS is to be developed as it is constructed using a three-phased timed approach. Phase 1, as described in Chapter 4, commences before ISS assembly in space begins and consists of a series of flights combining astronaut and cosmonaut crew activities on the Space Shuttle, Soyuz, and the Mir Space Station. The object of this phase is to gain in-orbit experience that will reduce the technical risk associated with assembly and operation of ISS in a manner analogous to the Gemini program that preceded the Apollo program. Phase 1 operations are controlled by Moscow mission control, while the Johnson Space Center develops the capability of monitoring Mir.

Phase 2 begins the assembly of ISS with the launch of the FGB tug in December 1997 on a Proton booster, closely followed by a Space Shuttle launch to attach a pressurized node that will serve as the interface to the U.S. side of the ISS and another Proton launch to deliver the Russian Service Module. The Service Module is very much like the current core module of the Mir Space Station. A Soyuz-TM crew-return vehicle arrives on the fourth flight and will permit the space station to have a permanent crew by providing a means for emergency return to Earth. A series of 10 more flights through mid-1999, five U.S. and four Russian, will complete Phase 2. (Phase 2 is complete when the U.S. Laboratory Module is completely outfitted with research equipment.) At this stage, one of the four large U.S.-provided PV arrays will be in place, and power will also be provided by arrays on the FGB and Service Module.

The third and final phase will complete the assembly with delivery of additional U.S. and Russian modules as well as additional PV arrays and other supporting hardware and systems. During Phase 3, the delivery of modules and components contributed by Japan (the JEM—a large pressurized laboratory and outside work platform), Russia (research modules), Canada (mobile servicing system with a robotic arm) and Europe (the COF, a laboratory module) will also take place. On completion of Phase 3, scheduled for 2002, a permanent human presence is planned for ISS with a six-person crew and an operational life of 10 years.

RESEARCH ON ISS

The ISS will provide accommodations for pressurized and unpressurized payloads as a means of satisfying users in both the scientific research and technology development areas. Three basic categories of U.S. payloads and prospective users exist: (1) pressurized microgravity and life sciences, (2) commercial and technology research, and (3) unpressurized external attachment payloads. The International Standard Payload Rack (ISPR) will be the primary location for pressurized payloads within the U.S., Japanese, and European modules on ISS. ISPRs have standard power, data, thermal control, nitrogen, waste gas, fire detection, and mechanical interfaces, and can accommodate about 1.5 m³ and 700 kg of equipment.

Research using the facilities provided by the international partners is likely to contribute significantly to the scientific and technical use of ISS. The Japanese contribution to ISS, the JEM, differs from the other ISS modules because, in addition to being able to house pressurized payloads, the JEM will have its own airlock that opens to an "exposed facility" where payloads that require placement outside the pressurized environment (such as for scientific observations, communications research, and materials exposure research) can be located. The JEM will also have a manipulator located outside the module that will enable the crew to both move payloads from the airlock onto the exposed facility and retrieve them without extravehicular activity. The NASDA payloads inside the JEM will focus on microgravity sciences (e.g., furnaces, electrophoresis, and protein crystallization facilities) and space life sciences research (e.g., cell culture equipment). The ESA plans to build and attach its COF to ISS and is currently planning facilities to conduct research in areas including human physiology (e.g., to study blood constituents and cardiopulmonary parameters), cell and tissue cultures (with the capability to fix and freeze samples and perform some analyses on-orbit), and microgravity sciences (e.g., to study materials at temperatures and to study fluid phenomena). ESA is also considering opportunities to conduct space science, Earth observations, and technology development research with payloads located outside the pressurized volume of ISS. Information on Russian payloads planned for ISS was not available, but Russia has indicated that the research areas prominent aboard Mir will be continued on ISS. Although providing world-class facilities for cooperative scientific research in space is a primary goal of ISS, major gains may come from the practical knowledge gained through other, more basic aspects of the program such as the assembly of the structure in orbit.

The following sections summarize NASA's current plans for ISS. Unlike the section in Chapter 4 that describes research that has been conducted over the last nine years on Mir, the following sections describe plans, intentions, and projected research that is scheduled to take place on new facilities on a new space station beginning in about 1999.

Space Life Sciences

The drive to understand gravitational influences on biological systems is emphasized by the predominance of life science experiments in the current plans for ISS. The life and biomedical science facilities are scheduled to begin to join the ISS in 1999 with the addition of the Gravitational Biology Facility and the Human Research Facility to the U.S. Laboratory Module. The primary role of each facility is to increase the understanding of gravity's influence on basic biological processes. Research using the Gravitational Biology Facility will focus on cell, plant, and developmental biology, whereas research using the Human Research Facility will focus on physiological adaptation mechanisms to microgravity.

The Gravitational Biology Facility consists of two ISPRs and modular specimen habitats. The combined mass of 700 kg includes generic research equipment, support systems, and analytical equipment needed to conduct research in cell, tissue, plant, and developmental biology. Human research will be conducted using the Human Research Facility which will focus on cardiovascular, neuropsychological, musculoskeletal, hematological, metabolic, and immunological areas of interest. It will consist of a suite of equipment contained in up to four racks which will be delivered to the space station over a six-year period. The intended primary use of this latter facility is to enable work towards the development of effective countermeasures to mitigate deleterious effects of space flight.

The Centrifuge Facility is scheduled to join ISS in 2001 with a four-arm centrifuge, and later in 2004 with an eight-arm centrifuge. The ability to enable research using whole animals and plants at gravity levels between zero g and 2 g on up to 8 habitats, will provide new capabilities and promote basic research on the influence of gravity on biological systems. NASA projects that the Centrifuge Facility and the Gravitational Biology Facility will eventually be able to house a variety of species for research. Several different modular habitats are planned to be able to maintain rodents; terrestrial plants in all phases of growth; fish, amphibians and aquatic plants; animal, plant, and microbial cell cultures and tissue cultures; bird and reptile eggs; and insects. Refrigerators and freezers will be on board to preserve samples prior to their return to Earth. The Life Sciences Glovebox will provide for animal and sample handling and help enable rapid turn-around experimentation. It will be accommodated in an ISPR, provide access for two crew members simultaneously, and will accommodate two of the modular habitats. Video display and the control panels are included internal and external to the facility.

Microgravity Sciences

Since the early Apollo missions, microgravity experimentation has been performed on materials and fluids systems. In fact, much of the design experience that

has gone into space station microgravity facilities has evolved over decades of Apollo, Skylab, Spacelab, and Shuttle flights. Early experiments in which astronauts rotated water drops before flight cameras evolved into drop dynamics, single-crystal and dendritic growth experiments, and surface-tension-driven convection experiments on Spacelab. On ISS this type of research will be pursued as part of the research program to be conducted in the Advanced Fluids Module of the Fluid Physics Dynamics Facility/Modular Combustion Facility (abbreviated as the Fluids/Combustion Facility). The planned Advanced Fluids Module experiment rack will consist of several experiment-specific test chambers, each carrying ancillary equipment such as cameras, laser optics, heaters, etc., to accommodate experiments in the areas of interface configuration, thermocapillary flow, particle dispersion, and gravity-jitter (the spectral range of oscillatory accelerations arising from crew motions, machinery, rocket firings, and so on occurring in orbiting spacecraft).

The Combustion Module will share a facility with the Advanced Fluids Module. It also has a history of evolution throughout the earlier days of U.S. space flight, being generated from sounding rocket, Space Shuttle mid-deck, get-away special, and Spacelab experiments. The Combustion Module will be contained in an experiment rack with several viewing ports to allow for various diagnostics as required by anticipated experiments in comparative soot-flow diagnostics, forced-flow flame spread, fiber-supported droplet combustion, and radiative ignition and transition to spread.

As mentioned above, the Advanced Fluids Module and the Combustion Module share the Fluids/Combustion Facility, the core of which will be delivered to the ISS in 1999. The Combustion Module will join the core at that time, but the Advanced Fluids Module will not be available until 2001. Along with the capability to conduct research on gases and liquids in the Fluids/Combustion Facility, the capability will also be available for research on solidifying systems such as ceramics, electronic materials and metals and alloys. The Furnace Facility will first become available for such experiments on ISS in 1999 and be completed by 2002. Similar to the Fluid/Combustion Facility, the Furnace Facility consists of a core rack that houses diagnostic controls, which will be delivered initially with an instrument rack. When completed with a second rack, it will contain a high-gradient furnace, thermophysical properties measurement furnace, magnetic damping furnace, and a general purpose Bridgman furnace.

The Biotechnology Facility will continue the studies to understand complex protein structures by having protein crystal growth as one of its two major program components. Cell tissue studies on mammalian tissue cultures and their response to microgravity will be supported by the second component of the program. The one-rack facility will contain support utilities for a variety of investigation-specific experiments and will become part of ISS in 1998.

The Microgravity Sciences Glovebox will provide the capability to manipulate samples within an enclosed environment and the flexibility for short-duration, rapid turn-around experiments. This glovebox will feature a command and monitoring panel and a video unit and will be accommodated in a modified ISPR. Although planned for

development by ESA, baseline planning has it originally interfacing with the U.S. Laboratory Module with future accommodation being feasible in the JEM and COF.

Space Sciences

In keeping with the goals of the NASA program to understand the evolution and makeup of planetary systems, two space science experiments are planned that will utilize the opportunity of the long-duration collection times provided by the Mir platform to both capture cosmic dust particles and examine the efficacy of capture media. These fall within the external attachment payload category for the Phase 1 (Mir) portion of the program and are designated the Mir Sample Return Experiment and the Particle Impact Experiment. To date, one space science experiment has been selected to fly on the ISS in 2001 as an attached payload. A joint project of NASA and the U.S. Department of Energy, the Alpha Magnetic Spectrometer (AMS) experiment will study the properties and origin of cosmic particles and nuclei originating from outside our galaxy and look for antimatter and dark matter. Current plans call for flying the experiment on a Space Shuttle mission in 1998 as a precursor to the work on ISS and for operating the detector for three years on ISS before it is returned to Earth. The AMS experiment is an international collaboration of 37 universities and laboratories. Beyond these experiments, the NASA Office of Space Science, which is responsible for research in astrophysics, space physics, and planetary science, currently does not have plans to use ISS for its research.

Earth Observations and Sciences

The ISS provides a platform for conducting ongoing Earth science programs for the NASA Mission to Planet Earth program. As noted earlier, ISS's inclination orbit (51.6°) permits frequent revisits to selected sites at the highly populated low and mid-latitudes. In addition, test sites can be imaged throughout the diurnal cycle, thereby permitting the investigation of short-lived phenomena such as the daily buildup of cloud cover or the response of vegetation undergoing drought stress. The Stratospheric Aerosol and Gas Experiment (SAGE) III is planned as an attached payload. Using the self-calibrating solar occultation technique, SAGE III will measure profiles of atmospheric aerosols, ozone, nitrogen dioxide, temperature, pressure, and water vapor. Lunar occultation observations will measure key nighttime species, nitrogen trioxide, and chlorine dioxide.

Space Technology Development

In order to increase commitment by U.S. industry and impact national competitiveness, commercialization and engineering will be allocated 40 percent of the resources for research by the time Phase 3 is reached in ISS development. This is reflected in a combination of research and development programs anticipated over the 1999-2002 time period incorporating a total of 33 space station racks, 13 in the U.S. Laboratory Module, 10 in the JEM and 10 in the ESA Attached Pressurized Module. Fourteen external sites with power and data will provide additional capability. An example of such an external payload is the Hydrogen Maser Clock.

Materials processing, biotechnology, materials and environmental effects and technology demonstrations will all be represented. A Commercial Protein Crystal Growth and a Generic Bioprocessing Apparatus will culminate many years of microgravity research experimentation by providing commercial products. Other planned commercial development programs include a demonstration of a solar-dynamic power module, processes for liquid-phase sintering, and superconductor materials in devices.

Highlights of the Differences Among Space Stations

This report has discussed the ISS and Mir and provided detailed information on these and other space stations and platforms. Some major differences between ISS and its predecessors stand out. Before describing some of these differences, it should be made clear that in comparing the capabilities of ISS to Mir and the Space Shuttle, we are largely comparing projections for the future with real data. For example, the ISS information describes what NASA and its international partners *intend to do*, while the other information describes what *has been done* and *is being done* in orbit.

The parameter of electric power is an enabling feature for space research, especially in the life and microgravity sciences, and it may be crucial to future efforts in technology development and commercial research. The low-user power levels on Mir have sometimes prevented the optimal use of onboard equipment for research. At the completion of ISS, the power level for research will be significantly greater than has existed on any previous space platform or than was projected for the SSF in its 1993 configuration. Once all sources of power are in place, ISS should be able to satisfy the large, intermittent demands of power-hungry equipment such as furnaces, as well as the lower but constant demands of components such as electric motors that will be used in refrigerators, freezers, and centrifuges.

The capacity of ISS to accommodate a permanent crew of six is double that of Mir and 50 percent greater than the previous plans for the assembly-complete configuration of SSF. The Space Shuttle routinely carries six or seven crew members but cannot stay in orbit permanently. The availability of crew members to conduct experiments remains contingent on the time that is needed to maintain and housekeep the station and will be difficult to project as accurately as many other parameters. However, it is clear that life sciences research is likely to benefit from the first-ever combination of long-duration missions, a large crew, and access to a wide variety of biomedical hardware in space—including a centrifuge facility to allow research on whole organisms in artificial gravity—as well as from relatively frequent opportunities to return samples to Earth.

The change in orbital inclination from that planned for SSF, 28.8° degrees, to 51.6° for the ISS, while advantageous for Earth sciences and remote sensing, has the disadvantage of limiting the payload weight capacity from non-Russian launch sites and shortening the launch windows for Space Shuttle launches. The high inclination has also necessitated the requirement for a number of complex on-orbit operations to provide enough electrical power to operate the space station and perform research during assembly. However, the high inclination allows Russian participation in the program, including multiple Russian launch systems, and this eliminates the complete dependence on the Space Shuttle for resupply and crew rotation that was part of the SSF program. ISS will be resupplied primarily by the Progress-M and -M2 spacecraft that will dock automatically to ISS. Therefore, a human crew will not be needed for routine missions to resupply ISS with propellant and other basic needs.

Last, the anticipated interior volume of ISS is almost double the pressurized volume that had been planned for SSF and is almost four times that of Mir. The capabilities for research on the SSF-derived portion of ISS will be approximately the same as were planned for SSF and additional capabilities—though not yet well-defined—are expected to be available from the Russian modules. The large size of ISS will require as many Space Shuttle flights as would have been necessary to assemble SSF as well as additional flights by Russian launch systems, but clearly promises to offer the opportunity for a large number of researchers from the partner nations to participate in the program. With the proposed U.S., Russian, Japanese, and European laboratory modules, as well as other facilities, and the robust system for logistical support of ISS, it will be possible to utilize the features of a long duration in space inherent to a space station without the power and other constraints faced currently on Mir and without the need to return to Earth after two or three weeks as is the case with the Space Shuttle.

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Appendix

National Research Council Commission on Engineering and Technical Systems Aeronautics and Space Engineering Board

Committee on the Space Station

Statement of Task

The Committee will review the design and program plan of the U.S. Space Station and identify engineering issues that would benefit from in-depth analysis. As it gains understanding of space station technical and programmatic issues, the Committee may recommend workshops or in-depth studies on specific issues of concern. The Committee will also accept suggestions from NASA for specific studies. The Committee may establish panels of experts, from within the Committee, from other NRC units, and from the aerospace community at large, to conduct these separate efforts. Panels will report to the complete committee as defined by their individual charters, and the Committee will provide written findings and recommendations as appropriate.

The Committee will meet 4-5 times each year to receive briefings from NASA and the space station user community on the status of the program. The Committee will prepare position papers and letter reports as appropriate, on issues that are deemed to be of general interest.

The Committee's findings and recommendations will be presented as reports to the NASA Associate Administrator for Space Flight, the NASA Administrator, relevant Congressional committees, and other concerned parties. These reports and position papers will be subject to National Research Council report review procedures prior to release.

October 1, 1991

The Committee on the Space Station Capabilities of the Space Station Freedom and Other Space Stations

Statement of Task

For each of the last several years, the Congress has debated whether to go forward with the NASA Space Station first proposed in 1984. Critics have often suggested that better options exist that could provide similar capabilities sooner or at a lower cost. Such options have included the Russian Space Station Mir, "free-flyers" that would be only occasionally visited by astronauts, and space stations that could be based on an augmented, extended-duration, Space Shuttle orbiter. The Committee seeks to provide information relevant to these questions by preparing an unbiased technical study of the characteristics and resultant capabilities of the proposed [near-term] space station options for the U.S.

The emphasis of the Committee's study and the resulting report will be on compiling and comparing technical parameters associated with the space stations in question, and on determining their significance with regard to the types of research most appropriate for a space station. The Committee will:

1. Review the basic technical characteristics of the Space Station Freedom and its proposed alternatives. This will include parameters such as overall power, pressurized volume, the quality of the microgravity environment, and the maximum crew supportable by the life support system.
2. Characterize the overall ability of each space station to accommodate experiment facilities by outlining the basic categories of flight hardware that can be supported by each design. The characterization of each design's capabilities will be based on two sets of data:
 - a) information regarding resources such as power, volume, and crew time that will remain for research and other activities after essential operations and maintenance are performed; and
 - b) existing technical specifications of flight hardware that has been flown on the Space Shuttle or other missions, and general technical requirements to support research on a space station.

The Committee's report should aim to serve as a resource for national decision-makers by comparing Space Station Freedom's capabilities to those of other proposed options for the U.S. space program by highlighting the important characteristics of each design. Since no agreed-upon set of requirements exists for a U.S. space station, the Committee will not make judgments as to which space platform is preferred, nor will the Committee speculate on the specific projects that could be supported by each station or evaluate each design for specific scientific uses.

May 28, 1993

